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REFERENCE

Lane, B. H., 1935, Suggestions to authors of papers submitted for publication by the United States Geological Survey: U. S. Geol. Survey, Washington, D. C. (For sale by Superintendent of Documents, Washington, D. C. 40c.)

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American Journal of Science

MAY 1957

GEOGRAPHY OF OLENID TRILOBITE DISTRIBUTION AND ITS INFLUENCE ON CAMBRO-ORDOVICIAN CORRELATION

JAMES LEE WILSON

ABSTRACT. A polar projection map showing Paleozoic tectonic belts of the western and northern half of the eastern hemisphere is used as a base on which to plot world-wide occurrences of Late Cambrian and Tremadocian olenid trilobites and to compare their position with that of typical North American and Oriental faunas of similar age. In the correlation scheme used, the American Dresbachian is equated with very late *Paradoxides* and pre-olenid faunas of Europe, the Franconian and Trempealeauan with Late Cambrian olenid faunas, and the lowest Canadian (Gasconade) with high Tremadocian.

The map and accompanying faunal data charts show that olenid trilobites the world over are apparently a dark-shale-and-limestone extracratonic fauna found in and near the borders of troughs which now almost in all cases coincide with Paleozoic mountain belts. Different faunas inhabited the major cratonic areas, e.g., the Siberian *Koldinia*, the Changshanian-Fengshanian, and the North American *Elvinia*, *Conaspis*, *Ptychaspis*, and saukid faunas. These are vertically more diversified, and the genera have shorter ranges than those in the geosynclinal belts where conditions were more uniform and evolution was slower. At various times expansion of trilobite stocks from the geosynclines across the craton resulted in genera preserved in both provinces; these afford some degree of correlation. The widely separated geographic and vertical occurrence of olenid and olenid derivative genera may be explained by this hypothesis. Probable transitional faunas between the major biofacies occurred along the cratonic borders of the geosynclines; these are now known only in exotic boulders or in beds sporadically exposed in tectonically complex areas. A postulated cause of the biofacies difference in the extracratonic belts is their turbid water and soft bottoms, indicated by the highly argillaceous dark sediments.

INTRODUCTION

This paper proposes an hypothesis to explain the wide distribution of the sharply segregated faunal provinces of the Cambro-Ordovician. It states that these result from basically different marine environments controlled by the position of continental cratonic areas and the paleogeography of geosynclinal belts surrounding them. Only the Upper Cambrian and Lower Ordovician faunas have been studied to develop this idea, but the thesis may perhaps be equally well applied to the Lower and Middle Cambrian and to the whole Lower Ordovician. During the past 50 years much has been learned about the strikingly varied trilobite faunas and strata in different parts of the globe. This has resulted in a rather vague picture of two Cambrian faunal realms termed the "Atlantic or Acado-Baltic" and "Pacific" provinces. Reconsideration of the basic facts of Cambro-Ordovician biogeography in conjunction with a map showing its relationship to the world's orogenic belts and major cratonic areas forms the basis of the hypothesis which attempts to demonstrate and explain a systematic biogeographic picture.

GENERALIZATIONS ON CAMBRO-ORDOVICIAN BIOGEOGRAPHY

1. Trilobites of the olenid family, and certain forms generally associated with them in the Scandinavian type area, are now known to be widely distributed in the world's orogenic belts or in outcrops between them and the major shield areas of the continents. For example, Cambrian trilobite faunas in Acadia and Massachusetts are identical with those of England and Scandinavia and are characterized by *Paradoxides* in the Middle Cambrian and olenids in the Upper Cambrian. This area was therefore long ago termed the Acadian or Atlantic province. But in late years olenid trilobites have been found in South America, western North America, and China, and the paradoxidian *Centropleura* has been reported from Siberia and eastern North America.

The clearest demonstration that well-developed olenid faunas are confined to geosynclinal areas comes from North America where faunas from both geosynclinal and cratonic areas are present and sufficiently well-known to invite comparison (Wilson, 1954, fig. 4; Palmer, 1956b, p. 663-681). A similar pattern of distribution is clear in comparing faunas of southern-eastern China with northeastern China, probably the second best known Cambro-Ordovician area where both faunal provinces are represented (fig. 1, compare A, AA, BB with 1a-1d). A second geosynclinal biofacies band across southern Siberia is suggested by the map, but the evidence is meager. The Tien Shan range south of the Angara shield contains strata with an olenid fauna (B on fig. 1). The presence of the paradoxidian *Centropleura* in the Kuznetsk basin (CC) and on the Maja River (DD) and Bennett Island (FF) apparently following the easterly trend of Caledonian and Late Paleozoic orogenic belts around the Angara shield indicates that these faunas may be confined to the areas off the craton. Belief in the idea of a Cambro-Ordovician biofacies belt between China and the Siberian Angara shield is strengthened by Lu's statement (1954a, p. 123) that Tremadocian-Argenigian faunas with *Birmanites* have been discovered in Sui-yuan province just south of Mongolia. This tectonic position is between the Sino-Korean cratonic area and the Angara shield.

In the writer's opinion it is unadvisable to extend the term "Atlantic" or "Acado-Baltic" province into regions scattered over all the world; therefore, the term olenid province is used in this paper to refer to these widely distributed, generally geosynclinal occurrences of olenid and associated genera in the Cambro-Ordovician. This name is inappropriate for Lower and Middle Cambrian faunas, and the more general term, extracratonic province, is suggested for such faunas as may occupy consistently paleogeographic and tectonic positions far off the edges of the world's cratons.

The hypothesis assumes the general permanence of continental nuclei and oceanic basins over the world since Cambrian time. The concept of accretionary buildup of the cratons by progressive orogeny around Precambrian cratonic areas is accepted. Indeed, the map (fig. 1) showing fairly consistent relationship between (1) faunal facies of Early Paleozoic, (2) Middle and Late Paleozoic orogenic belts, and (3) Tertiary orogenic belts leads one to infer stability of the basic cratonic areas throughout the last 500 million years.

2. Over the cratonic areas and on the continental margins of the geosynclines very different groups of trilobites exist. With present knowledge these may be grouped into two faunally related realms, one on the eastern hemisphere side (Siberia and Chinese cratonic areas) and the other on the western

Fig. 1.

side of the North Pole (over the Canadian shield and on its miogeosynclinal edges). These constitute what has been termed the "Pacific province," but they are termed cratonic provinces in this paper.

3. Strata containing clear representation of the two faunal facies are commonly found in close proximity. Earlier workers in New England attributed the juxtaposition of sharply defined faunal provinces of the Cambrian to the presence of intervening land ridges within the geosynclines (New Brunswick anticline of Schuchert). Later, more detailed, stratigraphic study in New England (Lochman, 1956a, p. 1352-66) casts doubt on the existence of such a feature, although field evidence shows that locally in Acadia such a barrier exists (Hutchinson, 1956, p. 309). Similar argument for a Tsinling-Korean barrier is advanced by Kobayashi to explain the radical faunal difference between the olenid-bearing strata of southeast China-Korea and the typical northern China (Shantung) fauna. Lu (1954a, p. 122) advances arguments against this because of the geographic pattern which the localities form. He favors an environmental difference to explain the situation.

The proximity of the provinces is almost always tectonically emphasized, e.g., in North America, along (1) Logan's line of thrusting in New England, (2) the overthrust Vinini facies in central Nevada, and (3) the Ouachita graptolitic facies of southern Oklahoma overriding the Arbuckle carbonate strata with Late Cambrian and Lower Ordovician shelly faunas. In fact with few exceptions the olenid province may be described as a biofacies associated with geosynclinal strata; it is found generally in highly faulted and folded strata thrust over or against rocks bearing trilobites of the cratonic province.

But an exact tectonic characterization of the provinces is not possible, for the lines of Paleozoic folding and thrusting do not perfectly coincide with the distribution of the olenid biofacies. For example, olenids are found on the Baltic edge of the Russo-Baltic shield east of the Caledonian geosyncline thrust belt, *Glyptagnostus* is found north of the Ouachita orogenic belt in western Tennessee, U.S.A.; the paradoxidian *Centropleura* is found on the Angara shield, and the *Eugonocare-Glyptagnostus*-olenid assemblage is found in Australia far west of the Tasmanian geosyncline, about midway between it and the main Precambrian shield area of the continent.

4. The Cambrian trilobite provinces are biologically sharply separated; only rare genera occur in common between the realms. In the Lower Ordovician the graptolite facies contains the olenid family, and such genera are almost unknown among the typical gastropod-nautiloid-brachiopod (shelly) facies. Yet an absolute biological separation of faunal provinces does not exist. There are certain widespread and distinctive individual genera such as *Irvingella*, *Proceratopyge*, and *Beltella*, which occur in both types of faunas and permit some correlation.

In North America faunas on the cratonic margins of the geosynclines are becoming known (e.g., the *Pseudosaratogia magna* fauna of the Franconian in the Shenandoah Valley, central Appalachians (Wilson, 1952) and the *Hungaia-Bienvillia-Eurekia* fauna of the higher Franconian and Trempealeauan of central Nevada (Palmer, 1956a, p. 22). These miogeosynclinal faunas are cratonic in general aspect but contain some genera unknown on the central

craton and suggest a gradual change of biofacies toward the geosynclinal axes. Traces of additional Cambrian faunas in the extracratonic parts of the geosynclines are found in exotic boulders embedded in graptolitic strata of the Lower and Middle Ordovician. Such faunas contain elements of both cratonic and olenid faunal provinces and include the *Hungaia magnifica* fauna of the Lévis boulders of Gaspé, and the *Olenaspella* ("*Parabolinella*") *evansi* fauna of the Marathon uplift in west Texas and of the southern Canadian Rockies. The structural complexity of the strata bearing these faunas does not generally permit clear sequences to be established, but the trilobite genera in them make plain their approximate position in established zonation in both provinces. Because such faunas offer the best evidence for correlation between the two provinces they are of the greatest importance. The writer conjectures that Middle and Late Cambrian faunas listed by Öpik (1956, p. 1-24) from Queensland constitute another example of "transitional faunas," in a position intermediate between the eastern Australian geosyncline and the northern Australian shield area.

5. In general olenid trilobites are found in rather uniform dark argillaceous limestone or in dark shale rather than in the more varied strata of the shield areas and miogeosynclines. Much more study of the depositional environment of geosynclinal sediments is necessary for an explanation of what influenced the faunas of these facies belts. Some conjectures on this subject are given at the end of this paper.

6. The trilobites inhabiting the olenid province are less varied than those occurring in strata within the cratonic areas. In the Late Cambrian and Early Ordovician of Europe and North America where the faunas are best known, approximately 80 genera are known from the olenid biofacies, whereas more than 180 have been named from the cratonic areas. While such a statement is subject to inaccuracies caused by varying taxonomic procedures of different paleontologists and by differences in accessibility and abundance of material, these figures are none the less significant.

Also trilobites in the olenid realm apparently are vertically less diversified, inferring a slower evolution. Rather generalized conservative olenid types (*Beltella* and *Parabolinella*) are found in the Tremadocian as well as in earliest olenid beds (*Olenus*). In the rare instances where olenids appear with trilobite faunas of the craton they tend to show little evolutionary change; e.g., the American species "*Parabolinella*" *evansi* and "*Parabolinella*" *incerta* both occur with trilobites of the *Aphelaspis* zone and with the *Hungaia magnifica* fauna of probable latest Franconian or Trempealeauan age. Though future better understanding of these forms may show differences, so far as is known little evolution occurred in the American olenids during the whole of Franconian time. Pointing to the same fact is the long range of *Proceratopyge* from probably latest Middle Cambrian through the *Olenus-Elvinia* zone. In contrast to the olenid province of Scandinavia where progressive evolution of a single family provides the basis of zonal differentiation (Westergard, 1922, p. 182-188)), in the cratonic provinces zonal boundaries are more sharply defined with large assemblages of genera belonging to varied families abruptly replacing each other in vertical sequence over wide areas. For example, dur-

ing the Franconian stage in the North America craton four or five faunizones are recognized—each of them based on ten to twenty genera.

STATEMENT OF HYPOTHESIS

Consideration of the above facts makes plain that the distribution of olenid and associated trilobites in the Late Cambrian and Early Ordovician time (1) is world wide and (2) is in or near geosynclinal strata which mainly lie in folded belts surrounding but farthest exterior to the cratonic nuclei of the continents. It seems obvious that the olenid family, the Ceratopygidae and certain agnostids evolved slowly and progressively in the extracratonic belts from the beginning of Late (*Aphelaspis*) time well into the Ordovician. Occasionally genera from this stock migrated onto the shield areas to mix with the quite distinct faunas dwelling there. This appears to have happened in North America (1) during *Aphelaspis* zone time, (2) in middle and upper Franconian, and (3) in very earliest Ordovician.

DISCUSSION OF CORRELATION

Recently Lochman (1956b, p. 446-448) has ably reviewed the present status of correlation between the olenid and cratonic provinces. The writer's correlation charts express a minor difference from Lochman's in placing the *Agnostus pisiformis* zone as a correlative of the *Aphelaspis* and post-*Aphelaspis*—pre-*Elvinia* faunas rather than of *Elvinia* zone age. This zone in Scandinavia is now known to contain the earliest occurrence of *Olenus* sensu stricto (Henningsmoen, 1956, p. 55), and the *Aphelaspis* and post-*Aphelaspis* (*Dunderbergia*) fauna in Nevada contains olenids, "*Parabolinella*" spp. (Palmer, 1956a, p. 19). Wilson (1954, p. 259) has reported *Olenus* (a fragment) and two olenid species previously assigned to *Parabolinella* in exotic boulders with *Aphelaspis* and associated genera as well as *Homagnostus obesus* and *Glyptagnostus* species.

Thus the correlation chart equates the first appearance of olenid trilobites in Scandinavian and North American areas. This follows immediately after the first appearance of aphelaspid-like trilobites which apparently occur earliest in the *Leiopyge laevigata* zone in Scandinavia with *Nericia*.

The Chinese-Korean correlations shown by the chart are influenced by recently published data by Lu (1954a, p. 132-152 and 1954b, p. 429-431), as well as by earlier work by Kobayashi and Endo. The *Chuangia* zone contains *Proceratopyge* and the aphelaspid genera, *Crepicephalus orientalis* Endo and *Mansuyella lilia* Endo (cranidium). The writer doubts that the *Chuangia* zone genera assigned to *Kingstonia* and *Crepicephalus* of the North American *Cedaria-Crepicephalus* zones are correctly identified. Thus the writer places the *Chuangia* zone higher than does Lochman and equates it with the zone of *Agnostus pisiformis*, agreeing in this with Kobayashi (1955a, p. 66) and with Lu. Recent discovery in Texas of *Chuangia* in the basal *Elvinia* zone of the Llano uplift supports this view (Bell, W. C., personal communication).

The chart also equates in age the *Hedinaspis-Charchaqia-Proceratopyge* fauna of the extracratonic belts of China and southern Siberia with the earliest Changshanian on the basis of common occurrence of *Proceratopyge* and cer-

tain agnostids, and on the belief that on a world-wide basis earliest aphelaspids and olenids are roughly contemporaneous. The *Hedinaspis-Charchaqia-Proceratopyge* fauna probably is a facies equivalent to faunas as young as the *Irvingella* horizon from associations reported in the Tien Shan area.

Below the widespread olenid-aphelaspid horizon lies an equally ubiquitous and widely correlatable series of faunas generally recognized as the approximate top of the Middle Cambrian. In Scandinavia *Centropleura*, *Anomocare*, *Agraulos difformis*, and *Solenopleura brachymetopa* are important elements occurring with the uppermost *Paradoxides forchhammeri*. Apparently this same fauna is widespread in Asia, known from northern Siberia, Bennett Island, northern Kazakhstan, and the Kusnetsk basin in southern Siberia. This fauna is not yet plainly known in China or Korea but apparently is clearly seen in Australia (Öpik, 1956, p. 20) where it forms the uppermost Middle Cambrian in Queensland, Selwyn Range Area (Devoncourt limestone). Here, as in Sweden, the agnostid *Leiopyge laevigata* is present in the fauna. This faunal horizon may be correlated in North America through the St. Albans (with *Centropleura*) with the Park shale of Montana and Secret Canyon-Hamburg formations of Nevada's Eureka district. In North America the fauna of these beds is generally agreed upon as the uppermost Middle Cambrian (Howell and Duncan, 1939, p. 1-10) and best termed the *Bolaspidella* zone (Palmer, 1954, p. 713). Further substantiation of this correlation is afforded by Öpik's (1956, p. 20) discovery of *Holteria* Walcott with the *Centropleura* fauna in Australia. *Holteria* is reported by Palmer (1956a, p. 18) from the Hamburg dolomite which bears the *Bolaspidella* assemblage.

Between the horizon of *Solenopleura brachymetopa-Centropleura-Bolaspidella* (Middle Cambrian) and that of *Olenus-Aphelaspis* (Upper Cambrian) occur several widely scattered faunas which cannot now be correlated properly from one cratonic area to the other and whose position relative to the Middle-Upper Cambrian boundary is thus in doubt. These include the *Cedaria-Crepicephalus* fauna in North America, the *Leiopyge laevigata* zone in Sweden, the Kushan fauna in China, and the O'Hara shale fauna in Queensland, Australia. All four faunas contain some genera of both series. An unconformity occurs above the *Leiopyge laevigata* zone, far above the *Cedaria-Crepicephalus* fauna—indeed above the *Aphelaspis* zone—in North America, in China below the Kushan, and in Australia below the O'Hara shale. At the present time correlation fails within the level of these faunas, some of which may be biofacies equivalents of others or even partial biofacies equivalents of the recognized Late Middle Cambrian.

The correlation charts presented here attempt to emphasize the possibility that the highest Middle Cambrian of the extracratonic provinces may have a partial biofacies equivalent in the *Cedaria-Crepicephalus* fauna of the North American craton. The other alternative is that an important hiatus occurs in the Scandinavian area between the Middle and Upper Cambrian beds, this time being represented in the North American craton by continuous sedimentation. The biofacies equivalence of the zones is not considered proved, thus the Middle Cambrian faunas are set off from the higher zones by a double

line. Nevertheless, the writer disagrees with the statement by Öpik (1956, p. 22) that:

> . . . the much disputed question of the boundary of the Middle Cambrian and the Upper Cambrian is settled: the Middle Cambrian *Laevigata* zone (in Queensland, Australia) is followed immediately by the basal *Cedaria* zone of the Upper Cambrian, which, in turn corresponds to the zone with *Agnostus pisiformis.*

The zone of *A. pisiformis* is olenid in character; *Cedaria* is, all over the western hemisphere, definitely preolenid. In the writer's view it is not a valid assumption that, because in Scandinavia two zones, *Leiopyge laevigata* and *Agnostus pisiformis*, occur between well-recognized Middle and Upper Cambrian, equivalent zones or even the same number of intervening zones must be found in other parts of the world. Faunal zones result from local ecologic influences, regional geography, and evolution of the biologic groups used. At some level of stratigraphic detail in a given region the influence of the first two factors is bound to obscure the orderly sequence of trilobite genera as seen in the area accepted as standard. Furthermore, ranges of individual genera may be expected to differ in the cratonic areas from those in the extracratonic belts where the basic trilobite stocks may be expected to have evolved earlier and lingered perhaps after migration of stocks in the cratonic areas.

Summarily, the following facts suggest that the *Cedaria* zone is a North American cratonic biofacies of the latest Middle Cambrian *Paradoxides* fauna. They do not prove this but mainly emphasize the close relationship of the *Cedaria* fauna to the established—agreed upon—Middle Cambrian.

1. The highest beds in Scandinavia containing *Paradoxides forchhammeri*, the *Leiopyge laevigata* zone, contain trilobites (*Nericia*) closely resembling the American aphelaspid genus *Labiostria* Palmer. These beds therefore show an overlapping of genera considered typically Middle and Upper Cambrian. In the North American cratonic province faunas, the interval between recognized Middle Cambrian and the aphelaspids contains the *Cedaria-Crepicephalus* faunas.

2. The *Centropleura* fauna of Bennett Island, Siberia and of the *Solenopleura brachymetopa* zone in Europe (*Paradoxides forchhammeri*) contains *Agraulos* (*Proampyx*) *difformis* and *A.* (*Proampyx*) *acuminatus*. In west Texas, the same or very closely related species assigned by the writer in 1954 to a new genus, *Nasocephalus*, occur in boulders containing *Cedaria*.

3. Exotic boulders in the Lévis shale of Quebec contain pygidia of the Middle Cambrian *Hemirhodon* and *Olenoides* and the *Cedaria* zone genera *Catillicephala*, *Bynumia*, *Blountiella*, and *Brassicisephalus*, indicating a closer age relationship of *Cedaria* and Middle Cambrian than generally assumed.

4. The general aspect of the Vermont *Centropleura* fauna at St. Albans is of the *Cedaria* zone. This fauna is correlated by Howell and Duncan with the pre-*Cedaria* Park shale fauna of Montana but in fact only slight difference is present between the faunas. This may possibly be due in part to an environmental difference presented by the shale of the Park and the limestone and shale of the Pilgrim (*Cedaria* zone) of Montana.

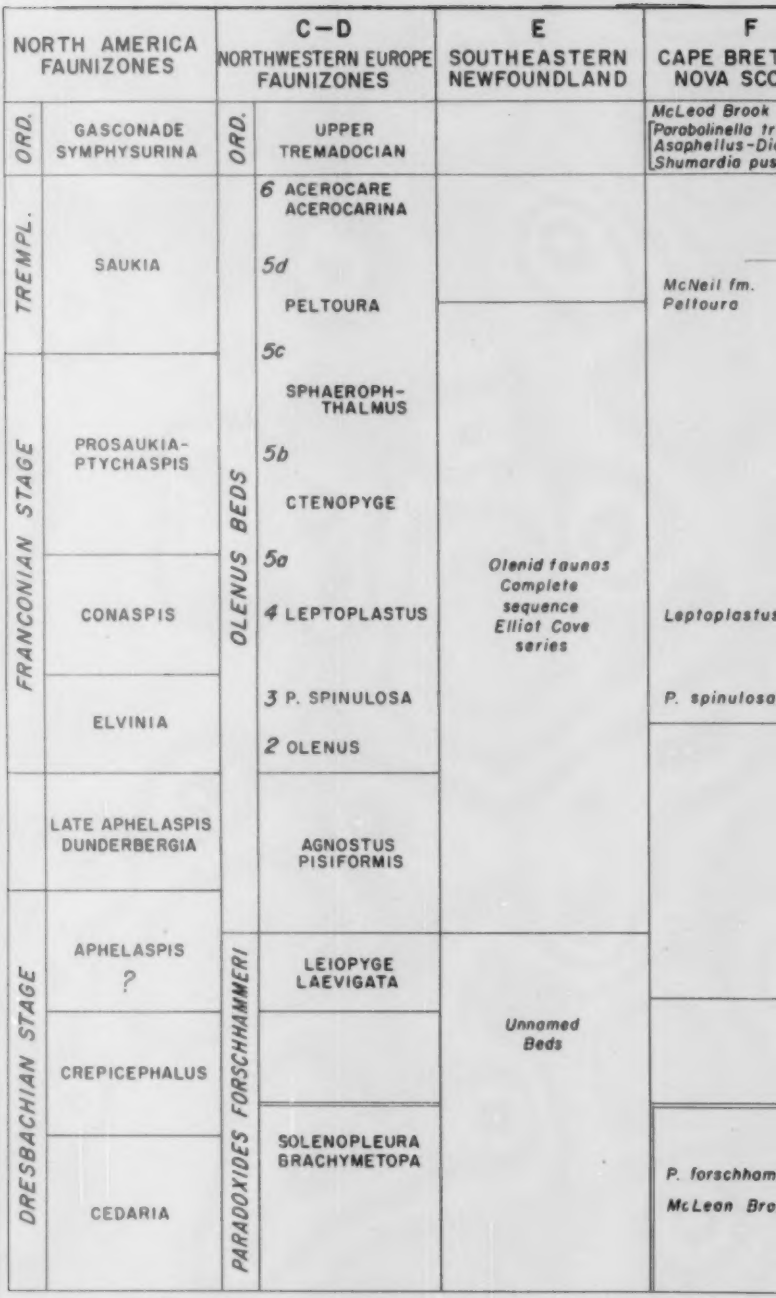
NORTH AMERICA FAUNIZONES
C–D NORTHWESTERN EUROPE FAUNIZONES
E SOUTHEASTERN NEWFOUNDLAND
F CAPE BRET NOVA SCO
ORD.
GASCONADE SYMPHYSURINA
ORD.
UPPER TREMADOCIAN
McLeod Brook
Parabolinella tr
Asaphellus-Di
Shumardia pus
TREMPL.
SAUKIA
6 ACEROCARE ACEROCARINA
5d
PELTOURA
McNeil fm.
Peltoura
5c
SPHAEROPH-THALMUS
FRANCONIAN STAGE
PROSAUKIA-PTYCHASPIS
5b
CTENOPYGE
OLENUS BEDS
5a
4 LEPTOPLASTUS
Olenid faunas Complete sequence Elliot Cove series
Leptoplastus
CONASPIS
ELVINIA
3 P. SPINULOSA
P. spinulosa
2 OLENUS
LATE APHELASPIS DUNDERBERGIA
AGNOSTUS PISIFORMIS
APHELASPIS ?
LEIOPYGE LAEVIGATA
Unnamed Beds
DRESBACHIAN STAGE
CREPICEPHALUS
PARADOXIDES FORSCHHAMMERI
SOLENOPLEURA BRACHYMETOPA
P. forschham
CEDARIA
McLean Bro

Fig. 2

F BRETON IS. SCOTIA	G NEW BRUNSWICK	H LEVIS SHALE BOULDERS	I WESTERN VERMONT GORGE FM.	J ALABAM CEDAR BL
Brook beds *lla triarthra* *us-Dictyonema* *a pusilla*	*Navy Island* *Dictyonema* *flabelliforme*	*Exotic boulder-band 4* *Symphysurina* *Diplapatokephalus* *Kainella-Loganopeltis*	*Highgate fm.* *Parabolinella— Symphysurina—Plicatolina*	
fm. *a*	*Peltoura scarabaeoides* *Sphaerophthalmus alatus* *Ctenopyge pecten* *Parabolina spinulosa* Narrows Fm	*Hungaia magnifica fauna-Gry. Limestone Not exactly correlated with either province; placed here on basis of No. American genera-Richardsonella, Stenopilus, etc— Loganellus, Parabolina incerta and Bienvillia are olenids*	*Middle Gorge fm. Hungaia magnifica fauna with new species showing probable evolution from older Franconian genera — olenids are "Parabolinella" evansi, Loganellus*	
astus *ulosa* McNeil fm. (dark sh.)	*Black Shale Brook* *Olenus s.s. sp.* *Homagnostus obesus* *Agnostus cove fm.* *A. pisiformis*	*Missing faunas in boulders*	*No faunas known from Lower Gorge*	*Glyptagnostus r* *Proaulacopleura* *Kobayashi = Aph*
hhammeri *Brook fm.*		*Numerous boulders from Métis and Grosses Roches Many No. Amer. genera also Olenoides pyg. and Hemirhodon (Middle Cambrian)*	*Hungerford slate* *Rockledge cong.* *Skeels corner* *Mill River cong.* Cedaria fauna *St. Albans sh.— Centropleura*	*fauna not well p* *May be associa* *Tricrepicephal* *and Kingstoni*

	K WELL-LAKE CO., W. TENN. HENDERSON #1, MARKHAM	L MARATHON FOLDED BELT	M YUKON–ALASKA BOUNDARY	N ROCKY MT. TRENCH SO. BRIT. COLUMBIA
		Low. Marathon fm. *Asaphellus – Beltella* *Symphysurina*	*Symphysurina* *Yukonaspis*	*Symphysurina* *Parabolinella sp.*
	900' of presumably upper Cambrian older than Knox			
		Olenid fragments & Geragnostus — **Dagger Flat fm.**	*not well placed* *"Parabolinella"* *punctolineata* *Ptychopleurites* *brevifrons* *Homagnostus* *subobesus*	
		Taenicephalus sp. *Wilbernia sp.* *Exotic boulder* *BC-2*		
		"Parabolinella" incerta *True olenid* *Exotic boulder* *SS-26*		*Lower McKay fm.* *(not well placed stratigraphically)* *"Parabolinella" evansi* *Dunderbergia sp.* *Glyptagnostus* *Homagnostus acutus*
ticulatus *buttsi* *laspid?*	*Glyptagnostus reticulatus, Oedorhachis* *2858 – 2862 ft.*	*"Parabolinella" evansi* *Glyptagnostus* *Homagnostus obesus* *Aphelaspis, Olenus sp.* *Exotic boulder BM-4*		
laced *ed with* *us*	*Oedorhachis* *Crepicephalid sp.* *Kingstonia* *2875 – 2904 ft.*			
	above Pre-Cambrian *2965 ft*	*Cedaria aff. C. gaspensis* *Blountia* *Coosella* *Nasocephalus* *Blountiella* *Coosia* — **Exotic boulders SS-24 32,33**		

	P CENTRAL COLUMBIA ANDES	Q EASTERN BOLIVIA NO. ARGENTINA	18 MENDOZA SO. ARGENTINA
	Kainella-Pseudokainella Westergardia or Cyclognathus	*Parabolina andina Parabolinella argentinensis-Kainella-Asaphids*	*Parabolinella fauna*
			Hungaia fauna Loganellus Triarthropsis
		Olenus argentinus fauna Correlation uncertain	*Elvinia Irvingella*
			Tricrepicephalus

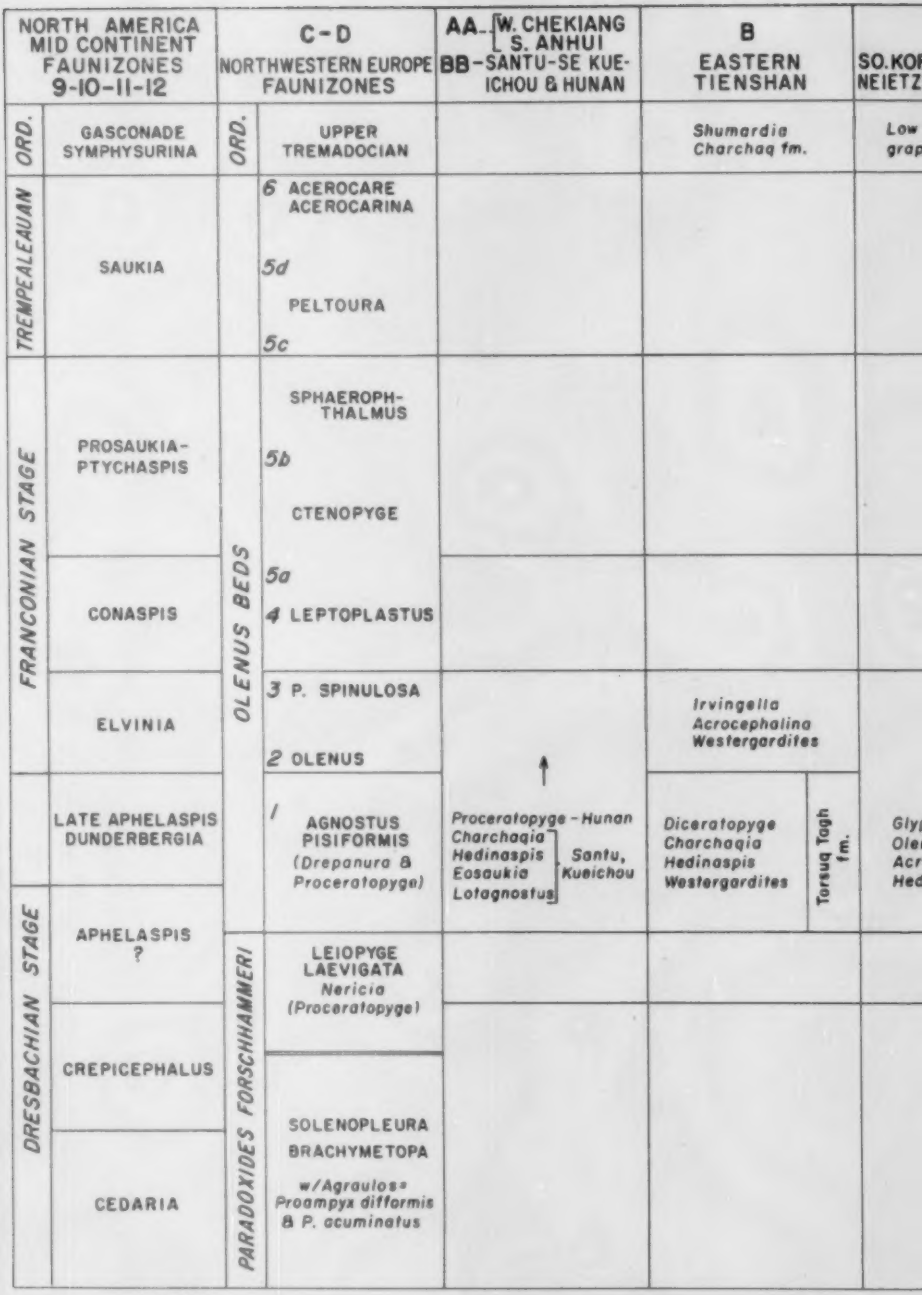
NORTH AMERICA MID CONTINENT FAUNIZONES 9-10-11-12
C-D NORTHWESTERN EUROPE FAUNIZONES
AA-BB- W. CHEKIANG S. ANHUI SANTU-SE KUEICHOU & HUNAN
B EASTERN TIENSHAN
SO. KOR NEIETZ
ORD.
GASCONADE SYMPHYSURINA
ORD.
UPPER TREMADOCIAN
Shumardia Charchaq fm.
Low grap
TREMPEALEAUAN
SAUKIA
6 ACEROCARE ACEROCARINA
5d
PELTOURA
5c
FRANCONIAN STAGE
PROSAUKIA-PTYCHASPIS
SPHAEROPH-THALMUS
5b
CTENOPYGE
5a
CONASPIS
4 LEPTOPLASTUS
ELVINIA
3 P. SPINULOSA
2 OLENUS
OLENUS BEDS
Irvingella Acrocephalina Westergardites
LATE APHELASPIS DUNDERBERGIA
1 AGNOSTUS PISIFORMIS (Drepanura & Proceratopyga)
Proceratopyge - Hunan Charchaqia Hedinaspis Eosaukia Lotagnostus
Santu, Kueichou
Diceratopyge Charchaqia Hedinaspis Westergardites
Torsuq Tagh fm.
Gly Ole Acr Hed
DRESBACHIAN STAGE
APHELASPIS ?
LEIOPYGE LAEVIGATA Nericia (Proceratopyge)
CREPICEPHALUS
SOLENOPLEURA BRACHYMETOPA w/Agraulos= Proampyx difformis & P. acuminatus
PARADOXIDES FORSCHHAMMERI
CEDARIA

Fig. 3

A O. KOREA-KOGENDA EIETZU & HEISYU DIST.	I-Ia-SHANTUNG PROV. SO. MANCHURIA SO. KOREA (PART) INNER MONGOLIA			Ib-TAHOPA-KWANGYUAN SO. SZECHUAN Ic-W. YUNNAN-PAOSHAN		Z NOVAYA ZEMLYA
Low Ordovician graptolite fauna	*Wanwan* *Ellesmereoceroids* *Saukids – Ord?*					
	Yenchou	*Dictyella* *Calvinella* *Saukia* *Pagodia*	Fengshanian	Paoshan Shale Ic	*Xenostegium* *Calvinella* *Saukia* *Quadraticephalus* *Tsinania*	
		Ptychaspis and Tsinania				
	Daizan	*Kaolishania* *Paramansuyella* *Conokephalina*	Changshanian			
		Irvingella *Changshania conica*			*Changshania*	*Irvingella* *Deckera vigilans* *Pesaia* *Koldinia* *Kaninia* *Agnostus pisiformis* *Dolgaia* *Orlovia*
↑ *Glyptagnostus* *Olenus asiaticus* *Acrocephalina* *Hedinaspis regalis*	Paishan	*Chuangia* *Aphelaspids* *Proceratopyge*			Ib	
	Kushan	*Drepanura* *Pseudagnostus* *Homagnostus* *Diceratocephalus* *Blackwelderia*			*Stephanocare*	
	↓ ?					

DD-MAJA RIV. FF-BENNETT ISL.	CC KUZNETSK BASIN SO. CEN. SIBERIA	3 KHATANGA-CHIRANDA R. EE-KANABAR MASSIF	4-VICTORIA ISL. CANADA 5-SO. CAN. ROCKIES		6-E. NEV., U 7-MONTAN
	?		*Parabolinella ("Moxomia")*		*Hystricurus* *Symphysurin* *Bellefontia*
	Apatokephaloides *Dictyites, Pagodia* *Pseudagnostus cyclopyge* *Homagnostus obesus*	3 *Esseigania tolli and Plethopeltis*	*Briscoia* *Plethopeltis(?)* *Prosaukia*	*Goodsir Group*	*Bowmania* *Eurekia* *Briscoia* *Elkia* *Euptychaspis* *Calvinella* *Richardsonella* *Tostenia=olenid* *Bienvillia=olenid* *Saukiella* *Richardsonella* *Leiocoryphe=* *Hungaia magnifi fauna*
		3-*Loc. E. of Kobayashi*			*missing?*
	Acrocephalites *Orlovia* *Koldinia* *Pseudagnostus cyclopyge* *Agnostus pisiformis*	*Schmidtaspis* *Koldinia* *Modocia=Deckera* *Lecanopleura, Bowmania=Cliffia*	4 *Elvinia* *Berkia & Elvinia* *Iddingsia* *Kaninia* *Irvingella*		*Elvinia fauna* *"Parabolinella"* *Olenus sp.?*
		3a-*No. Kazakhstan Aphelaspis fauna Proceratopyge*	*Dunderbergia=Megadunderbergia Kob.*		*Dunderbergia faun* *"Parabolinella" n. s. p.*
					Aphelaspis
					7 *Crepicephalu fauna*
Agnostids, numerous genera *Centropleura* *Anomocare* *Proampyx difformis* *Proampyx acuminatus =Nasocephalus Wilson?*	*Agnostids of Centropleura age* *Anomocare* *Other trilobites of upper Paradoxides age undetermined*	EE *Agnostids-3 genera* *Centropleura* *Anomocare* *Solenopleura* *Corynexchus*			7 *Cedaria fauna*

V., UTAH NTANA		8 SO. N. MEX.-ARIZ.	13-CEN. APPALACHIANS 14-ADIRONDACKS, N.Y.	15-MURPHY CREEK EAST GASPE 16-W. NEWFOUNDLAND COW HEAD
curus surina ntia		*Kainella* *Bellefontia*	*Hystricurus* *Bellefontia*	
pis nella olenid olenid nella he= gnifica a	Windfall fm.		*Tellerina* *Plethometopus*	
g?		8 *So. New Mexico* *Briscoia* *Prosaukia* *Chariocephalus* *Ptychaspis striata*	*Saratogia–Hoyt fm.* *Prosaukia*	
auna nella" p. ?	Dunderberg sh.		*Conaspis* *"Parabolinella"* *Taenicephalus* *Elvinia*	
gia fauna lla" 2 p.		8a *S.E. Ariz. top of Abrigo ss* *Dytremacephalus*	*Pseudo-saratogia magna fauna*	
pis				
phalus a				15–16 *Crepicephalus* *Cedaria* *not clearly separated*
ria a			*Crepicephalus–Cedaria* *(not clearly separated)*	HH *Centropleura belli Hutchinson* *Dartmouth R. Quebec*

REFERENCE KEY TO CORRELATION CHARTS AND MAP

A. South Korea
Kobayashi, T., 1944.

B. Eastern Tien Shan
Troedsson, G. T., 1937.

C. Scandinavia
Westergard, A. H., 1947.
Henningsmoen, G., 1956.

D. England
Stubblefield, C. J., 1956.

E. Southeast Newfoundland
Howell, B. F., 1925.
————, 1926.

F. Nova Scotia
Hutchinson, R. D., 1952a.

G. New Brunswick
Hayes, A. O., and Howell, B. F., 1937.

H. Levis shale boulders
Rasetti, F., 1943.
————, 1944.
————, 1945.

I. Vermont
Shaw, A. R., 1951.
————, 1952.
Gilman, M. N., 1955.

J. Alabama, Cedar Bluff
Kobayashi, T., 1936a.
Butts, C., 1926.
Resser, C. E., 1938.

K. Lake County, Tennessee
Bridge, J., personal communication, Feb. 1952.

L. Marathon folded belt, West Texas
Wilson. J. L., 1954.

M. Yukon-Alaska boundary
Kobayashi, T., 1936b.

N. Rocky Mountain Trench, Southern British Columbia
Kobayashi, T., 1938.

O. Hot Creek Range, Northwestern Nevada
Palmer, A. R., 1956b.

P. Central Columbia
Harrington, H. J., and Kay, M., 1951.

Q. Bolivia—Northern Argentina
Harrington, H. J., and Leanza, A. F., 1943.

AA. Western Chekiang Province, Southern Anhui Province (Chuhsien)
Lu, Y. H., 1954a.

BB. Southeastern Kueichou (Santu), Hunan-Lanhsi, Yuanling (Chinchoufu)
Lu, Y. H., 1954a.

1. Southern Manchuria,
Southern Korea (part)
Endo, R., and Resser, C. E., 1937.
Kobayashi, T., 1933.
————, 1935b.
————, 1955a.

1a. Shantung Province, China—Inner Mongolia
Sun, Y. C., 1935.
Lu, Y. H., 1954b.

1b. N Szechuan and Western Yunan, Paoshan, China
Lu, Y. H., 1954a.

1c. Indo China
Saurin, E., 1956.

1d. Thailand
Report to Cambrian symposium, 20th Geological Congress, Mexico, 1956.

2. Novaja Zemlya
Walcott, C. D., and Resser, C. E., 1924.

3. Khatanga—Chiranda River basins, Siberia
Kobayashi, T., 1943.
3a. Northern Kazakhstan, Siberia
Ivshin, N. K., 1956.
3b. South Iran
King, W. B. R., 1930.
4. Victoria Island
Specimen of Elvinia collected by Canadian Geological Survey.
5. Southern Canadian Rockies
Kobayashi, T., 1938.
———, 1955b.
6. Eastern Nevada
Palmer, A. R., 1956a (in Nolan et al).
Kobayashi, T., 1935a.
7. Montana
Lochman, C., and Duncan, D., 1944.
Lochman, C., 1950.
8. New Mexico
Flower, Rousseau, 1953.
9. Llano Uplift, Texas
Bell, W. C., and Barnes, V. E., 1957.
10. Arbuckle-Wichita Mountains, Southern Oklahoma
Frederickson, E. A., 1956.
11. Ozark Dome, Missouri
Lochman, C., 1956c.
12. Croixan Type Area
Bell, W. C., Berg, R. R., and Nelson, C. A., 1956.
13. Central Appalachians
Wilson, J. L., 1952.
14. Adirondack regions, New York
Fisher, D. W., 1956.
15. Murphy Creek, Eastern Gaspe peninsula and Cowhead, west coast of Newfoundland.
Kindle, C. H., 1948.
16. Western Newfoundland
Lochman, C., 1938.
17. Durness limestone, Northern end of Scotland
Stubblefield, C. J., and Evans, J. W., 1929.
Neaverson, E., 1956.
18. Mendoza, Argentina
Rusconi, C., 1954.
Centropleura Faunas
CC. Kuznetsk Basin, south central Siberia
Kobayashi, T., 1943.
DD. Maja River, extreme eastern Siberia
Kobayashi, T., 1943.
EE. South side of Anabar massif
Kobayashi, T., 1943.
FF. Bennett Island, Arctic sea, north of New Siberian Islands
Kobayashi, T., 1943.
GG. European area
Westergard, A. H., 1950.
Hupé, P., 1953 (in Piveteau).
HH. Eastern Gaspe
Hutchinson, R. D., 1952b.
II. Northwestern Vermont
Howell, B. F., 1937.

A glance at the distribution of the *Paradoxides* (*Centropleura*) fauna indicates that it is mainly extracratonic where it occurs in Europe, and in the Siberian and Appalachian areas (Hupé, 1953, Figure 96). If the environmental control hypothesis is correct, *Centropleura* or some form related to it might be expected to occur high in Middle Cambrian and lower Dresbachian strata in the Cordilleran geosyncline where extensive exposures of these beds

are known. Such has never been reported, but these faunas in Utah and Nevada, the critical areas, are not well known.

The best single horizon for world-wide correlation between the olenid and cratonic provinces at present appears to be the distinctive genus *Irvingella*. Much study of this only slightly varying genus has been made in North America where many "species" have been described on slight variants of its general form. The komaspid relationship of the genus has also been discussed by Resser, Kobayashi, and Lochman. In point of fact the genus is remarkably uniform and amazingly widespread in both cratonic and extracratonic occurrences:

1. N. America: ubiquitous in cratonic faunas, in many varied rock types with *Elvinia*.	ranges from middle *Elvinia* zone to the acme of development at top of this zone and into basal *Conaspis* zone.
2. S. America, Mendoza, Argentina edge of Andean geosyncline.	with *Elvinia*
3. Sweden — rare in olenid beds on edge of Caledonian geosyncline	*Leptoplastus* zone 4 and *Parabolina spinulosa*, zone 3
4. England	lower Upper Cambrian
5. Novaya Zemlya	*Koldinia* fauna
6. Tien Shan, Tibet	with Franconian-appearing forms and olenid *Hedinaspis*.
7. In Manchuria and NE China	*Changshania conica* fauna

Irvingella belongs to a family, Komaspidae, which is remarkably long-lived, ranging from Middle Cambrian through the whole Lower Ordovician. Apparently this hardy stock was also adaptable to a variety of environments, and thus during Upper Cambrian times was widespread over the globe even into the geosynclinal environment. However, it is found more characteristically in the cratonic faunas.

In *Conaspis* zone time a family (Parabolinoididae) basically derived from the olenids invaded the North American craton, as demonstrated by Lochman (1956b, p. 454). That olenids lived throughout Franconian time in the North American geosynclines is demonstrated by their presence in the *Hungaia magnifica* fauna. Rasetti has reported "*Parabolinella*" *incerta* from the Lévis boulders, and *Bienvillia* is a more specialized olenid also known from these faunas. The genus *Loganellus* of this fauna is probably olenid-derived. These genera plus an olenid identified as "*Parabolinella evansi*" are reported from the middle Gorge formation in unpublished work by Miss Mary Gilman. *Bienvillia* is known from the *Hungaia* fauna, probably of high Franconian age, in Nevada (Palmer, 1956b, p. 677). Possible traces of the *Hungaia magnifica* fauna are also known in geosynclinal edge positions in the Marathon

fold belt (Wilson, 1954, boulder BC-2) and in Kobayashi's fauna from the Yukon-Alaskan boundary which includes *Ptychopleurites brevifrons, Homagnostus subobesus,* and *"Parabolinella" punctolineata.* Rusconi has reported the fauna from Mendoza, Argentina, also in a geosynclinal edge position.

The North American Trempealeauan beds are characterized by extensive evolution of families indigenous to the craton, the later saukids, eurekids and ptychaspids. So far as is now known the only olenid found in the latest Cambrian is *Bienvillia,* whose species, *B. corax,* is reported from the Appalachians, Texas, and Nevada.

An exposition of the environmental and tectonic influences on Lower Ordovician faunas is given by Kobayashi (1955b, p. 383-397). The Cordilleran Lower Ordovician Pogonip, Garden City, McKay, and Mons formations contain olenids (*Beltella, Eulomella, Parabolinella, Peltoura, Parabolinopsis*) and such associated "European" genera as *Apatokephalus* and *Shumardia* mixed with *Symphysurina,* hystricurids, pliomerids, and other forms typical of the North American shelly facies. Similar faunas are found in the calcareous graptolitic facies of the Lower Ordovician, the Marathon formation of west Texas. Lochman (1956a, pl. 8, fig. 23) reports *Parabolinella* from the slate belt Ordovician east of the Hudson River in New York state. Rasetti (1943, p. 101-104) and Shaw (1951, p. 97-114) have described Tremadocian-like faunas from the northern Appalachians.

DISCUSSION OF SUBPROVINCES

Within the major extracratonic belts and across the cratonic provinces an obvious geographic differentiation of faunas exists. It appears that the widely distributed olenids and associated genera are divided into three geographic provinces each with more or less typical genera:

1. North Atlantic or Acado-Baltic with *Olenus* sensu stricto, *Parabolina, Proceratopyge, Peltoura,* and Tremadocian genera.
2. Andean-Cordilleran—mainly known in the Lower Ordovician-Tremadocian with *Parabolinopsis, Parabolinella,* and certain distinctive asaphids, and in the Upper Cambrian with *Parabolinella*-like olenids.
3. The Asiatic and Australian with *Hedinaspis* (*—Papyriaspis?*) *Charchaqia, Proceratopyge, Olenus s.s.*

The associated agnostids appear to be much more ubiquitous, e.g., the same or closely related species of the genera *Glyptagnostus, Homagnostus,* and *Pseudagnostus* are found in all olenid subprovinces.

Similarly, subprovinces exist over the cratonic areas. As the Oriental and Canadian cratonic faunas become better known, more similarities are seen between them. Nevertheless, the two provinces contain distinctive faunas; and further, the Late Cambrian Oriental cratonic faunas may be separated into the *Koldinia* (Siberia) realm and the Changshanian-Fengshanian realm (China and Manchuria). The American Late Cambrian cratonic faunas are more uniform and constitute a general area with correlation easily possible from Arctic Canada to Texas.

PATHS OF MIGRATION

A corollary to the hypothesis of environmental control of olenid distribution is that migration of olenids and the cratonic "Pacific" faunas must have followed paths along environmentally favorable trends. Assuming that in general Cambrian trilobites lived in shallow water, the olenid family and its associates or their larvae migrated only along the extracratonic belts. Future conjectures about migrations and distribution of Late Cambrian trilobites should be guided by recognition of the position of the geosynclinal belts, particularly those which appear immediately south of the main boreal continental nuclei.

From examination of the presented map (fig. 1) it is possible to make a reasonable conjecture about the pathways of distribution of the Late Cambrian olenid faunas from Europe to the Orient. That a definite connection existed between the two areas is strongly indicated and has been known since the study of Troedsson (1937) on the Quruq Tagh faunas of the Tien Shan. In Australia and Korea, olenids (*Hedinaspis* or *Papyriaspis*) appear possibly as early as Late Middle Cambrian (Öpik, 1956, p. 19). Conversely, *Proceratopyge* has been found in Scandinavia as low as immediately pre-olenid (*Leiopyge laevigata*) and in the Orient only with genera typically of olenid age. *Drepanura* is a genus of olenid age in Europe but immediately pre-olenid in age in Asia (Kushan fauna). Lack of exact correspondence in ranges of the Scandinavian and eastern Asiatic genera may be due to insufficient collecting or to time involved in migration of genera from one area to the other. This problem is not yet solved but at least close connection is demonstrated by the above and many other genera.

Distances between the known occurrences of European and Asiatic olenid faunas are great: Poland to the Tien Shan is 2500 miles and from the Tien Shan to southwestern China almost as far. Two possible paths of interconnection of these faunas exist between Europe and Asia. (1) Possibly the connection existed around the northern edge of the Russo-Baltic shield from the Caledonian geosyncline to the Uralian and southward to the Tien Shan. The presence of cratonic faunas in Novaya Zemlya and in northern Kazakhstan argue against the Uralian connection. (2) More probably olenid faunas followed a favorable extracratonic facies southward from the western edge of the Russo-Baltic shield and eastward in an early Paleozoic "Tethys" geosyncline. A redlichid and paradoxidian faunal province is known across the Mediterranean belt, from southern Europe through the Middle East. Late Cambrian olenids are not known across southern Europe (Gèze, 1956, p. 209), because the strata are thin and unfossiliferous or missing, but Tremadocian graptolitic beds are known in Sardinia. The great parallelism of olenid and *Paradoxides* beds over Europe and Acadia and the persistent latitudinal orogenic belts trending across Europe to the Orient suggest this major geosynclinal belt as the logical facies path to the Orient. South of this early Paleozoic Tethys on the edge of the Arabian shield in Persia appears a Late Cambrian Changshian biofacies (King, 1930, p. 316-327), with *Chuangia* overlying an *Anomocare* fauna of latest Middle Cambrian age typical of Kazakhstan and northern Siberia (3b).

EVIDENCE OF CLIMATIC ZONATION IN THE CAMBRO-ORDOVICIAN

It is obvious from orientation of olenid subprovinces that little coincidence or parallelism exists with the present equator. Yet in general the olenids mark a circumpolar path lying south of the main continental nuclei, and the cratonic provinces appear to be also circumpolar within these extracratonic belts. This might indicate a general climatic control except that olenid-bearing geosynclinal belts also cross the present equator in both hemispheres, trending from southern China to eastern Australia and from western North America to the southern Andes.

Wherever cratonic areas occur south of the geosynclines surrounding the world's large boreal cratons the northern cratonic faunas appear. Thus in Persia at the north edge of the Arabian shield a *Chuangia* fauna has been reliably recorded, and over the northern Australian shield area Öpik records a "Pacific" or "Oriental" fauna (1956, p. 268-270), indicating genera identical with those in China. Rusconi (1954, p. 3-60) has recently described typical "North American" genera *Tricrepicephalus, Elvinia, Irvingella, Hungaia,* and *Loganellus* from a marginal cratonic position between the major southern Andean geosyncline and the Patagonian cratonic area. Of these genera the first three are purely cratonic in North America, and the last two are marginal cratonic, reported from the Appalachian and Cordilleran geosynclines. The presence of such well known "boreal" genera so far south in the southern hemisphere demonstrates that the modern equator did not influence the migration of marine faunas in Cambro-Ordovician times.

EXPLANATION OF ECOLOGIC CONTROL OF CAMBRO-ORDOVICIAN TRILOBITE DISTRIBUTION

The following primary ecologic factors must be considered in attempting to reconstruct the Cambro-Ordovician geosynclinal environment which formed characteristic rock types and was favorable to the distinctive olenid and similar faunas:

1. Tectonics and geography of land areas within or marginal to the subsiding extracratonic belts. These influence the amount and kind of terriginous clastics brought into the trough which in turn control the firmness of sea bottom and turbidity of water, both important factors in marine ecology.

2. The geography of the basins of deposition, their shape and size, and access to oceanic waters. This major factor controls tidal and other currents, wave action, and salinity of water.

3. Regional climate; this, in part, affects salinity of sea water and the amount and type of terriginous influx. This factor is not considered pertinent to the particular problem because of the world-wide distribution of the biofacies and lack of evidence for any equatorial climatic zone.

4. Depth of water. This primary factor controls temperature, circulation and turbulence and oxygenation of the water. It also influences degree of light penetration to the sea floor which in turn affects the abundance of microflora close to the bottom. Depth thus indirectly partly controls the amount of living benthos, and the rate of oxidation of decaying organic matter on the sea floor.

Perhaps, most important, deep water means a stable relatively unchanging environment.

In general, the rock types characterized by the fauna are dark shale and argillaceous limestone. The limestone may contain up to 10 or 15 percent clay or finely disseminated silica and is typically dark with high organic content, thin and laminated bedding, some bedded dark chert, and a limited and sporadically distributed fauna, poor in number of species, but, in some layers, rich in number of individuals.

A full ecologic interpretation is not attempted here, but only brief comments on some of the more important controling factors.

1. It is a reasonable conjecture that the Early Paleozoic dark argillite facies represents somewhat deeper water deposition than does the cratonic facies, but that this is a simple and full explanation for the biofacies difference is open to question. The "slate belt" sections of the Appalachians (northwestern Vermont, and Frederick and Conestoga formations of Maryland and Pennsylvania), and the shale-limestone sequence of the Marathon formation in Texas contain pebble conglomerate lenses, rare small bioherms, cross-bedded silt laminae, and thin sandstone beds, in all reasonably indicative of shallow water deposition. The carbonate, orthoquartzite, and gray-green shale sections which in North America characterize the cratonic Cambro-Ordovician all contain abundant evidence of shallow water deposition also. The best evidence for deeper water deposition of the black argillite beds off the craton is their abundant fine lamination, which really indicates quiet water conditions. Perhaps, more persistent marine water of only slightly greater depth occurred in the extracratonic areas. This would result in more uniform and continuous sedimentation. It is possible that with turbidity only slightly deeper water was necessary to make such factors as light penetration, plant life, oxygenation of bottom and amount of benthonic life quite different in the extracratonic areas from the shelf conditions. Water was still sufficiently shallow to form common shallow structures in its sediments.

2. The interior areas of geosynclines are conceived of as highly unstable, with rapid subsidence and local uplifts generally in linear patterns, and with much volcanic activity. Despite this, the dark argillite facies of the Early Paleozoic is in many places not interbedded with typical eugeosynclinal graywacke sandstone, and does not, therefore, necessarily represent either deltaic deposition or filling of deep water troughs from rising highlands, but merely quiet water deposition of organic rich muds. Yet, for some reason, as this lithofacies is developed on the cratonic margin, it gradually, but persistently, excludes the cratonic faunas and favors the presence of olenids and associated genera and, in the Ordovician, also graptolites. One may conjecture a persistent source of fine sediment into the extracratonic troughs from material off the distant cratons which by-passed the miogeosynclinal and marginal cratonic basinal areas. A second source of fine mud may have been volcanic islands on the oceanward sides of the troughs. This characteristic Cambro-Ordovician argillite facies might be termed eugeosynclinal, but in all three major geosynclinal belts of North America, it is probably somewhat thinner than the limestone-dolomite, shale, and sandstone sections of the miogeosynclines

(Wilson, 1952, fig. 4; Wilson, 1954, fig. 2; Palmer, 1956b, fig. 2). Further, in North America direct evidence is lacking of volcanic activity associated with the extracratonic argillaceous facies, although the commonly associated bedded dark chert may derive indirectly from submarine weathering of ash falls (Goldstein and Hendricks, p. 421-42). Similar dark argillite and limestone facies bearing olenids are known in the Orient (Machari facies of Kobayashi) and in the Tasmanian-Victorian geosyncline, as well as in the type olenid area of Scandinavia.

3. One may conjecture that soft-bottom conditions in the geosynclinal areas are chiefly responsible for the biofacies change seen, but they alone were probably not a prime factor because the varied rock types in which cratonic faunas are found indicate that nektobenthonic trilobites were well-adapted to soft-bottom conditions. A pertinent example is the distribution of the well-known *Elvinia* fauna which consists of about 25 genera found in both geosynclines and in almost all exposures of Late Cambrian rocks across the marginal cratonic areas in the midcontinent United States:

Location of Elvinia Fauna	*Rock Type*
1) Southeastern California	green shale and limestone nodules.
2) Dunderberg shale, Nevada	brown shale and nodules of limestone, massive limestone.
3) Montana and northern Wyoming	crevices between algal stromatolites and in shaly beds.
4) Wisconsin and Minnesota	greensand and conglomerates.
5) Llano uplift, Texas	light colored bioclastic limestone and conglomeratic calcareous sandstone.
6) Missouri, Ozark dome	very fine grained gray limestone.
7) Central Appalachians, Pennsylvania	dark intraformational pebble conglomerate and bioclastic limestone.

Although the *Elvinia* fauna occurs in extremely varied rock types representing undoubtedly many types of sea bottom, it is apparently absent in the Appalachian and Ouachita geosynclinal deposits which consist mainly of dark limestone interlaminated with shale.

In a general way the morphology of trilobite species in the extracratonic belts shows that soft bottom and quiet water conditions prevailed in these troughs. The small blind agnostid genera, presumably mud burrowers, are much more common in the olenid province than in the strata over cratonic areas. Further, many important olenid and other extracratonic genera appear built for buoyancy above a possibly murky, muddy sea floor—they possess characteristically wide flattish shields with abundant fragile spines on pygidia, thoracic segments, and free cheeks. Examples include the Ceratopygidae, *Hungaia*, *Kainella*, *Briscoia*, *Centropleura*, *Paradoxides*, Olenidae and Asaphidae. In contrast many genera both in the China-Siberia and North American cratonic areas appear adapted for shallow, somewhat turbulent water over a variety of bottom conditions. These trilobites generally show high relief, are

commonly pustulose, and possess fewer spines which are generally stout and blunt. Conversely cratonic genera may be clearly adapted for burrowing and may possess smooth tests, reduced number of thoracic segments, and well-rounded genal angles and pygidial edges (e.g., *Araphoia, Camaraspis, Kingstonia, Tsinania*).

A clear statement on trilobite morphology as related to ecology is now premature, for Cambro-Ordovician trilobite paleontology has been concerned over the last few decades primarily with description of the myriad of species present in these strata, and not with their ecology. Numerous exceptions to the above generalizations are known. However, some of them may prove the rule. For example, the writer suggests that *Dikellocephalus* is a member of the cratonic saukids with a morphology much like that of typical extracratonic trilobites. Where present over the cratonic areas the genus occurs in fine clastics (Lodi siltstone in Wisconsin, Point Peak shale in Texas). It is fairly clearly a specialization of the saukid family adapted to soft-bottom conditions.

4. It may be that the continuous presence of suspended fine sediment in the water of the extracratonic troughs was a more important factor than either depth of water or soft-bottom conditions. The olenid and associated genera may have inhabited waters of persistent turbidity, of muddiness far greater than known on the cratonic regions where repeated shallowing of the water allowed changes in bottom currents and turbulence, and periodically washed out fine material. Deposition was essentially continuous in the troughs. In such an environment continuous soft bottoms would result, purely benthonic (filter-feeder) organisms could not thrive, and deposition would constantly entrap and preserve unoxidized organic matter.

The analysis given by Lochman (1956a, p. 1352-66) to account for the facies change from the cratonic Lower Cambrian faunas to the *Elliptocephala* fauna of the Taconic sequence in New York is in general agreement with the writer's concepts outlined above. She indicates predominantly soft mud bottom, slightly deeper, stiller, and more poorly lighted waters, possibly with a warm oceanic derived current in the extracratonic Taconic trough.

SUGGESTIONS FOR FURTHER STUDY

1. More phylogenetic taxonomy and more taxonomy with consideration of world-wide literature is necessary. Further refinement of correlation charts and biogeographic provinces depends upon world-wide identification of genera, and upon establishing them in families.

2. Environmental interpretation of Cambrian and Lower Ordovician trilobite morphology is needed. For example, practically nothing comparable to Whittington and Evitt's (1954) work on Middle Ordovician forms has been done on older trilobites.

3. Better understanding is required of the depositional environment of the dark shale and limestone (graptolitic facies) so widespread in the Cambrian and Ordovician in the geosynclinal areas.

Many of the ideas suggested in this brief paper cannot be adequately documented in the present status of Cambro-Ordovician paleontology. The main purpose has been to point out the important geographic coincidence be-

tween olenid distribution and the extracratonic mobile belts of the earth's crust. The evidence bearing on this is especially incomplete in Siberia where the writer's references are 15 years old. Furthermore, the valuable Australian papers in the 20th International Geological Congress Cambrian symposium by Öpik have important bearing on the problem but were not used in formulating the map presented in this report. It is anticipated that the present paper will open some immediate controversy concerning world-wide correlation and faunal province delineation. It presents its hypothesis in hopes that Cambrian paleontologists, stimulated by the present symposium of the 20th International Geological Congress, will bring forth data to verify or negate some of the ideas presented here.

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AGE OF GLACIER PEAK ERUPTION AND CHRONOLOGY OF POST-GLACIAL PEAT DEPOSITS IN WASHINGTON AND SURROUNDING AREAS*

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ABSTRACT. Volcanic ash, which occurs as a single layer in more than 200 post-glacial peat bogs in the State of Washington, is correlated with a similar layer of volcanic ash in alluvium and bogs of Idaho, Montana, southern Alberta, and southern British Columbia. Based on the known localities of occurrence, the ash at the time of deposition covered an area of at least 180,000 square miles. Vertical and horizontal grading of the layer show that the eruption that produced the ash was single and short. The source of the ash, as demonstrated by the distribution of occurrences, petrographic similarity, and horizontal grading of the particles, is Glacier Peak, an obscure volcano of the Cascade Range in north-central Washington.

The ash is composed of 85 percent glass and 15 percent crystals, the latter of which consists of plagioclase, hypersthene, hornblende, magnetite, and a trace of augite. A progressive decrease in particle size, improvement of sorting, and decrease in crystal and heavy mineral content with increasing distance from Glacier Peak preclude the possibility of any source for the ash other than Glacier Peak.

The age of the ash layer, as determined by radiocarbon dating of peat immediately underlying the ash at two localities, is 6,700 years. This age is of particular significance as it serves as a prime reference for establishing an absolute chronology of post-glacial events over a wide area in the Pacific Northwest.

Additional radiocarbon analyses of peat resting on glacial outwash at the bottom of two bogs and in the bottom sediments of Lake Washington in the Puget Sound Lowland place the withdrawal of the Vashon ice sheet from west-central Washington at more than 13,650 years ago. Owing to a considerable time lapse between ice retreat and deposition of the peat dated by C-14, we can conclude only that the Vashon recession is pre-Mankato in age. Precise assignment of the Vashon glaciation to one of the pre-Mankato substages of the Wisconsin glaciation recognized elsewhere must await the results of further radiocarbon dating in the Puget Sound area.

INTRODUCTION

The occurrence of a distinct layer of volcanic ash in the sediments of post-glacial peat bogs in the State of Washington has been known for many years (Rigg and Richardson, 1938; Hansen, 1947). A recent investigation of the peat resources of the State by G. B. Rigg and M. T. Huntting resulted in the discovery of a single layer of volcanic ash in about 200 bogs ranging geographically from the United States-Canadian border on the north to Tenino on the south and from the western side of Puget Sound to the eastern boundary of the State. Further studies by Gould and Budinger (in preparation) of Lake Washington, a deep, post-glacial lake near Seattle, reveal a layer of volcanic ash in 30 sediment cores from the lake bottom. A similar layer of volcanic ash has been reported also in the bogs of southern British Columbia, Idaho, and Montana by Hansen (1939; 1948; 1950; 1955) and in Recent alluvium of northwestern Montana and southern Alberta by Horberg and Robie (1955). Figure 1 shows the known distribution of this ash layer and the localities of occurrence. Most of the ash occurrences are in the glaciated areas of Puget Sound and northeastern Washington where the most intensive field work has been done and where bogs are more numerous than in areas not invaded by continental ice.

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Hansen has shown on the basis of pollen profiles that this ash layer has the same time-stratigraphic position in all bogs bored by him (fig. 1), and he has concluded that the ash layer resulted from a single eruption of one of the Cascade volcanoes. The most probable source, as suggested by Hansen (1947) is Glacier Peak, a somewhat obscure volcano just west of the crest of the Cascade Range in north-central Washington.

Based (1) on the assumption that the retreat of Vashon ice from Washington began about 18,000 years ago, and (2) on post-glacial rates of peat sedimentation along with certain archaeological and geological data, Hansen estimated the age of the volcanic ash layer and the Glacier Peak eruption at 6,000 years. Largely from these ages and pollen profiles, he established a chronology of post-glacial forest succession and climate in the Pacific Northwest.

In order to test the suggestion of Hansen that the ash layer in the bogs is of the same age and from the same source, namely Glacier Peak, an intensive study of the field data on the ash occurrences was made, and physical and petrographic properties of representative samples of the ash along several lines of traverse were studied. Furthermore, the age of the ash layer in two bogs, Moss Lake Bog and Covington Bog (fig. 1) near Seattle, was determined by radiocarbon dating of the peat immediately underlying the ash layer. In addition, samples of peat immediately overlying the glacial sediments at the bottoms of these bogs and a sample of peat overlying the glacial sediments in the bottom of Lake Washington were dated by Carbon–14 analysis. These determinations establish the ages of the basal peat at the sampling sites and provide minimum dates for the recession of the Vashon ice sheet from these localities. This work places the post-glacial chronology of peat sedimentation and related stratigraphic studies in Washington and adjoining areas on a more precise basis than was possible before the advent of radiocarbon dating.

Most of the field work on which this report is based was done from 1949 to 1953 under the direction of Rigg for the State of Washington Division of Mines and Geology. Both of the authors participated in the collection of peat samples for radiocarbon dating and of volcanic ash samples from selected localities for laboratory study. The investigation of sedimentary and petrographic features of the ash and interpretation of results was done by Gould.

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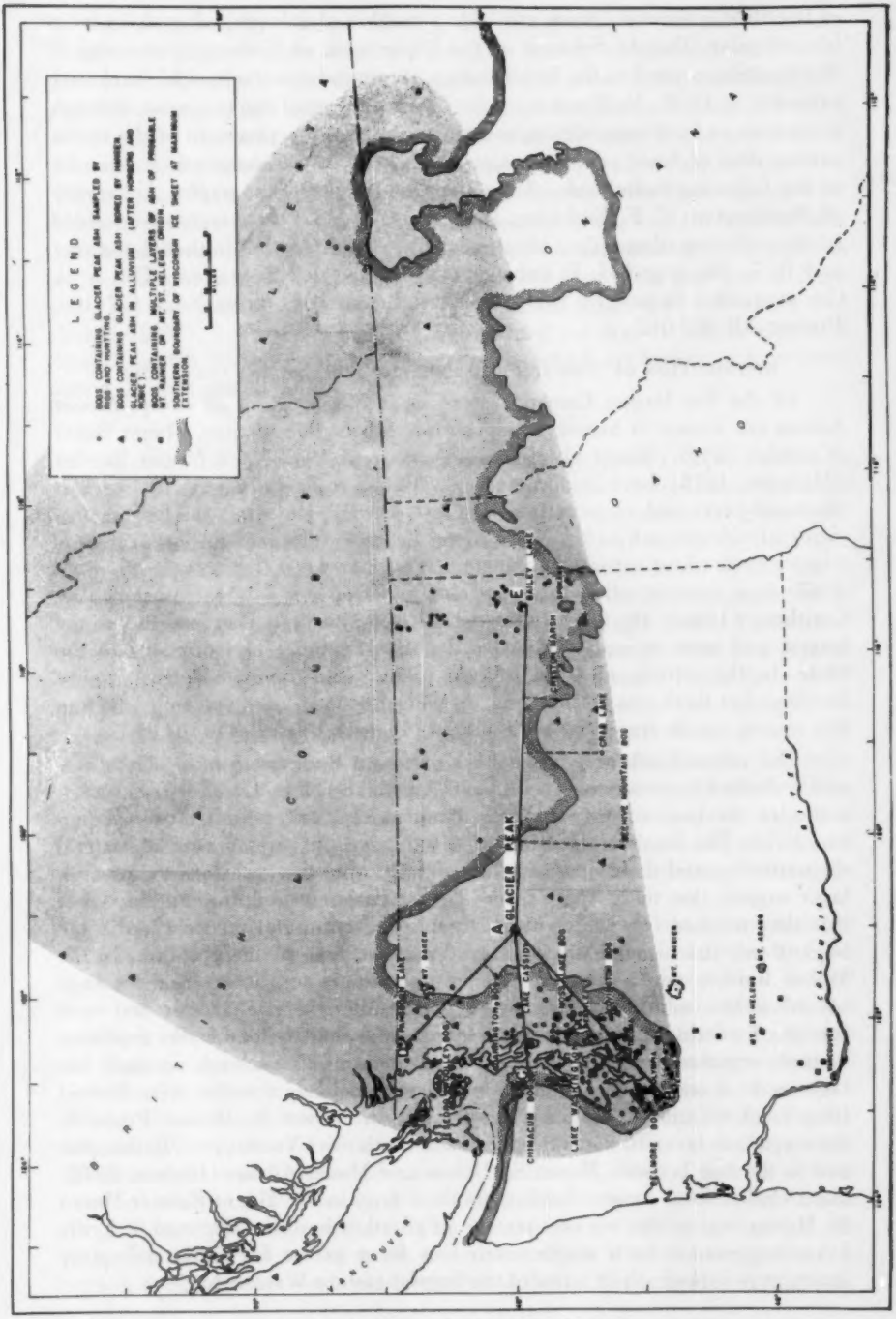

Fig. 1. Index map showing localities of Glacier Peak ash in peat bogs and Recent alluvium in Washington and surrounding areas.

of the State, graciously made available a number of volcanic ash samples from his collection. Dwight Schmidt of the Department of Geology, University of Washington, assisted in the identification of mineral species. Special thanks are extended to D. R. Mullineaux of the U. S. Geological Survey, who, through discussion end correspondence, contributed to the interpretation of the radiocarbon date of basal peat from Covington Bog. Acknowledgment is due also to the following individuals of the Department of Oceanography, University of Washington: T. F. Budinger, D. M. Ragan, and J. L. Amidon who aided in the collection of samples; Miss Jean Stilwell who assisted in the laboratory; and D. R. Doyle and H. E. Babcock who drafted the illustrations. This work was supported in part by Office of Naval Research Contract Nonr 477(10), Project NR 083-012.

DISTRIBUTION OF THE ASH AND RELATION TO CASCADE VOLCANOES

Of the five largest Cascade volcanoes in Washington, all except Mount Adams are known to have ejected volcanic ash in Recent time. Mount Baker (Coombs, 1939), Mount St. Helens (Verhoogen, 1937), and Mount Rainier (Mathews, 1914) have been active on a minor scale during the past several thousand years and as recently as the last century. However, the largest producer of volcanic ash of the Washington Cascade volcanoes in Recent time is Glacier Peak whose activity culminated an estimated 6,000 years ago (Hansen, 1947) in a great eruption that dispersed ash over a wide area. As shown by Carithers (1946), the pyroclastic debris from this eruption constitutes the largest and most extensive mineable deposit of pumice and pumicite in the State. In the vicinity of Glacier Peak, pumice and pumicite deposits a few hundred feet thick rest on the youngest glacial deposits, and volcanic ash from this source can be traced on the Columbia Plateau 100 miles to the east.

The volcanic ash in the peat bogs of figure 1 occurs in most places as a single distinct layer unmixed with peat above and below. Locally, however, in a few of the bogs of eastern Washington more than one ash layer was encountered. The local distribution of the upper layer or layers, their lateral discontinuity, and their similarity in composition to the lowest continuous ash layer suggest that these upper layers do not represent multiple eruptions, but that they resulted from subsequent stream excavation and redeposition in the bogs of ash that accumulated subaerially at the time of the eruption. In the Mount Rainier and Mount St. Helens areas there are, however, three bogs which contain multiple layers of ash, each differing in character and each forming a continuous layer in the bogs. It is clear that these layers represent multiple eruptions and perhaps more than one source. Although no study has been made of samples from these layers, it appears likely that they were derived from local eruptions of Mount Rainier and/or Mount St. Helens. Probably the single ash layer in the two bogs to the south near Vancouver, Washington and in the bog between Mount St. Helens and Mount Adams (Hansen, 1942) has a similar local source. Aside from these bogs in the Mount Rainier-Mount St. Helens region, the ash occurrences in all other localities depicted in figure 1 are represented by a single continuous layer except for additional spotty layers of reworked ash in a few of the bogs of eastern Washington.

As suggested by Hansen (1947), the occurrences of this ash layer are roughly distributed about Glacier Peak as a center. Measured from Glacier Peak, the ash extends a maximum distance of 125 miles to the southwest; 120 miles to the west; 225 miles to the northwest on Vancouver Island; 250 miles to the north in southern British Columbia; and 450 miles to the northeast in Montana and southern Alberta. Other occurrences of volcanic ash in bogs near Edmonton, Alberta and in central British Columbia have been reported by Hansen (1949a; 1949b; 1955). Most of these contain a surface layer of ash, which has been correlated with the Mount Katmai eruption of 1912, and one or two deeper ash layers of unknown origin. It is possible that one of these may be correlative with the Glacier Peak ash as suggested by Horberg and Robie (1955), but Hansen (1949a) has pointed out that the source may well have been the British Columbia Coast Ranges which are known to have been active in post-glacial time.

THICKNESS OF THE ASH

West of the Cascade Range the ash layer ranges from 1/16 to 3 inches in thickness. In general it becomes thinner as the distance from Glacier Peak increases. For example, in the bogs of the Seattle area, about 60 miles from Glacier Peak, the ash averages about 1 1/2 inches thick, and in the bogs near Olympia, 120 miles from Glacier Peak, the average thickness of the ash is about 1/2 inch. Northwestward from Glacier Peak, the ash ranges in thickness from an average of about 1 1/2 inches in the Puget Sound Lowland to only a trace in the bogs of Vancouver Island. Although there is a general thinning of the ash with increasing distance from Glacier Peak, there is by no means a uniform progressive thinning with distance. For example, the layer of ash in Darrington Bog, 26 miles west of Glacier Peak, is only 1/2 inch thick, whereas the ash layer in one of the bogs near Olympia, 120 miles from Glacier Peak, is 1 inch thick. These local variations probably result in part from differences in the amount of ash deposited in the bogs directly from air fallout owing to local variations in air currents and rainfall and in part to inequalities in the amount of ash flushed into the bogs by streams and slope wash from adjacent land areas.

To the east and north of Glacier Peak, the ash layer ranges in thickness from 1 to 30 inches and is generally much thicker than in bogs west of the Cascade Range. In bogs within a 100-mile radius east of Glacier Peak, the ash averages about 4 inches in thickness, whereas in bogs 100 to 200 miles east of Glacier Peak the ash averages about 10 inches thick. Still further to the east in Montana and Alberta the ash layer thins to about 1 inch in bogs and about 9 inches in alluvium (Horberg and Robie, 1955). In the bogs of southern British Columbia directly north of Glacier Peak, Hansen (1955) reports that the ash layer is several inches thick. Although these data show no general trend in thickness of the ash layer as a function of distance, they do demonstrate that a great deal more ash was carried to the north and east of Glacier Peak than to the south and west.This fact together with the widespread distribution of the ash to the north and east confirm Hansen's suggestion that strong southwesterly winds must have prevailed at the time of the eruption.

A similar variability in thickness of pumice has been noted in Oregon from the Mount Mazama eruption (Williams, 1942) and in Argentina of the ejecta from the eruption in 1932 of the Chilean volcano, Quizapu (Larsson, 1937). In these areas the irregular dumping of ash resulted, evidently, from local cross winds and complex eddies. Local rainfall (mud rain) may have contributed also to the variable thickness of ash in these areas. Variations in the thickness of the ash in the bogs surrounding Glacier Peak appear to result not only from such local irregularities in air currents and rainfall but also from inequalities in the amount of ash flushed into the bogs by land drainage during the eruption.

STRATIGRAPHIC POSITION OF THE ASH IN BOGS

Most of the bogs in which the ash layer occurs occupy kettles or other depressions in the glacial drift. Following the retreat of the ice, the lakes which filled these depressions became the sites of deposition of stratified sediments of meltwater origin. In some bogs the meltwater sediments consist of blue clay and in others of stratified sand and gravel as in Covington Bog (fig. 2) which is typical of many of the Washington bogs. Later on, as the meltwater streams became blocked or changed their drainage, these lakes became the sites of organic deposition. In the deeper parts of the lakes the organic sediments consist chiefly of planktonic organisms, commonly referred to as limnic peat (Voss, 1934), sedimentary peat (Rigg, 1940), or gyttja (Twenhofel, 1939); and in the shallower marginal parts of the bogs the sediments consist of the remains of sedges, reeds, and other attached plants known as fibrous peat (Rigg and Richardson, 1938). As the lakes became filled with these deposits, the sedges and reeds gave way to sphagnum moss, the remains of which form

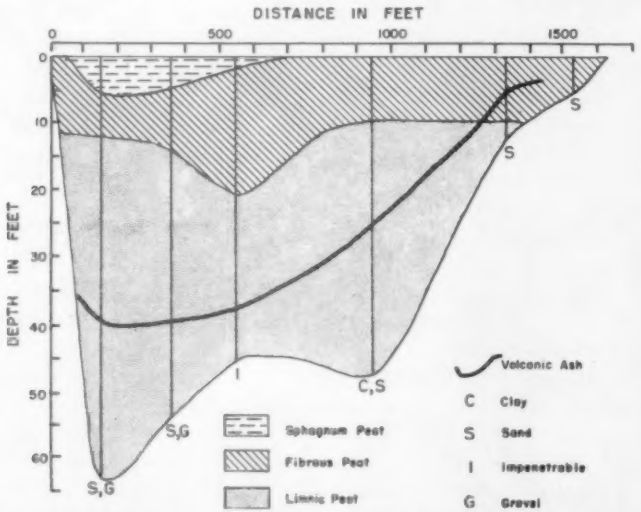

Fig. 2. Profile of Covington Bog showing the relationship of the ash layer to limnic, fibrous, and sphagnum peat. Vertical lines indicate borings on which the profile is based. Thickness of ash not to scale.

a deposit known as sphagnum peat. Thus the typical Washington bog is characterized by a sequence of beds consisting of glacial meltwater sediments at the base overlain by limnic peat, fibrous peat, and sphagnum peat.

That many of the bogs in Washington and surrounding areas were lakes at the time of ash deposition is shown by the occurrence of the layer of volcanic ash in limnic peat in central parts of the bogs and in fibrous peat near the bog margins. However, in about half of the bogs the ash layer occurs entirely within fibrous peat, indicating that in these localities the ash was deposited either on the exposed surface of the bog or in very shallow water.

In studies of pollen profiles of 34 of the bogs distributed throughout the area of figure 1, Hansen observed that the ash has the same time-stratigraphic position and that it was deposited in the post-glacial Xerothermic period.

COLOR AND TEXTURE OF THE ASH

The ash ranges in color from white to light gray in the limnic peat and from tan to brown in the fibrous peat. The tan to brown color results from oxidation of mafic minerals owing to subaerial exposure of the ash either at the time of deposition or at some subsequent time. A similar oxidation of subaerially exposed pumice in the vicinity of Glacier Peak and Mount St. Helens has been noted by Carithers (1946) and of the Mount Mazama ash in the vicinity of Crater Lake by Williams (1942).

The ash layer in the bogs is vertically graded, ranging from fine sand and coarse silt-size at the base to fine silt-size at the top. In general, the brown ash in fibrous peat is less well graded than the white or light gray ash in limnic peat. To demonstrate this, ash layers from several of the bogs were each divided into three increments from top to bottom, and mechanical analyses were made of each increment. The extreme results of these analyses are demonstrated by two samples, one of brown ash in fibrous peat from a depth of 10 feet below the surface of Pangborn Bog and the other of white ash in limnic peat from a depth of 215 feet below the surface of Lake Washington and 15 feet below the bottom of the lake. The median diameter of the ash particles in the Pangborn Bog sample ranged from 47 microns at the base to 28 microns at the top, whereas the median diameter of the ash particles in the Lake Washington sample ranged from 170 microns at the base to 10 microns at the top. This difference in grading is clearly a function of the depth of the water in which the ash was deposited. The poor grading of the Pangborn layer shows that the ash was deposited in shallow water or perhaps on the exposed surface of the bog, whereas the excellent grading of the Lake Washington layer shows that it was deposited in deep water. The oxidation of the Pangborn sample further suggests that the ash was deposited on the bog surface or was subsequently subjected to subaerial weathering possibly by a lowering of lake stage.

The variable thickness of the ash layer in adjacent bogs and even in individual bogs shows that the ash was not all deposited directly from air, but that a great deal of it must have been flushed into the bogs by streams and slope wash from adjacent land areas. That these processes must have occurred almost simultaneously is confirmed not only by a single layer of pure ash in

sharp contact with peat above and below, but also by the vertical grading of the particles from coarse to fine in the layer. These same features show that the eruption which produced the ash layer was a single blast and of short duration. Had there been any considerable lag between the direct fallout of ash from the air and that contributed by runoff, the ash would be represented by multiple graded beds interstratified with peat. Furthermore, multiple eruptions separated by long intervals would have resulted in similar stratification. On the other hand, if flushing by streams of large quantities of ash into the bogs had continued long after the eruption or had the eruption been continuous and long, the resulting layer would have consisted of coarse particles at the base overlain by an ungraded section and this in turn overlain by fine particles, all liberally mixed with peat accumulating at the same time. As these conditions do not prevail, it is concluded that the eruption which produced the ash was single and short and that the air- and water-transported ash must have been deposited in the bogs almost simultaneously.

To test Hansen's suggestion that Glacier Peak was the source of this ash, physical and petrographic properties of 14 samples were studied. One of these

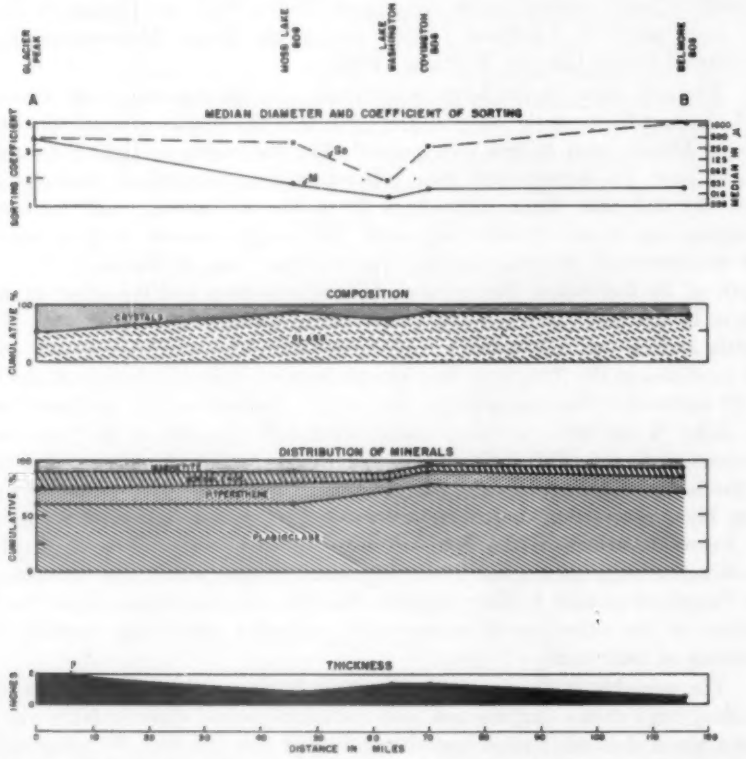

Fig. 3. Section southwest from Glacier Peak showing sedimentary and petrographic features of the ash layer.

consists of pumice sand and ash a few miles west of Glacier Peak and the others of volcanic ash from peat bogs located on four lines of traverse (fig. 1) radiating in several directions from Glacier Peak. The results of this study (figs. 3-6) show that the ash is not only vertically graded but that it is horizontally graded as well. Except for minor local variations, the median particle diameter of the ash decreases progressively with increasing distance from Glacier Peak. For example, in section A-B (fig. 3) the median diameter decreases from 500 microns at Glacier Peak to only 24 microns at Belmore Bog, 116 miles to the southwest, and in section A-E, the median diameter decreases from 500 microns at Glacier Peak to 22 microns at Bailey Lake, 173 miles to the east. Furthermore, the sorting of the particles becomes progressively better in most sections as the distance from Glacier Peak increases. This is well illustrated in section A-E (fig. 6) where the coefficient of sorting decreases from 3.46 at Glacier Peak to 2.00 at Bailey Lake. The exception to this generalization noted in section A-B (fig. 3) is probably a result of local sorting within the bogs or lakes themselves. Such local effects probably would not appear had the analyses been made of composites of several samples from each bog rather than of individual samples.

At and near Glacier Peak, the ash is not only coarse but also has a large range in particle size. Owing to the selective deposition of coarser particles near the source, the particles deposited at greater distances from Glacier Peak are finer and more uniform in size. Hence, the decrease in coefficient of sorting with increasing distance from Glacier Peak is related to the decrease in particle size.

In northwestern Montana and southern Alberta, Horberg and Robie (1955) state that the ash has an average grade size of coarse silt, and for one mechanically analyzed sample they report a median diameter of 50 microns. This is somewhat coarser than would be expected from our results. As the ash described by them occurs as stream and alluvial fan deposits, it is entirely possible, however, that the finer material has been winnowed away, thus accounting for this anomaly.

COMPOSITION OF THE ASH

The ash consists of glass and free mineral crystals. Based on 14 samples examined, the average glass content is 85 percent, and the average crystal content is 15 percent. The glass shards are irregular, splintered, and threadlike in shape. Many are clouded by inclusions of crystals and bubbles. Commonly the bubbles are ovoid or tubular in shape which gives the shards a shredded or fibrous appearance. The refractive index ranges from 1.502 to 1.515 and averages about 1.505. This suggests, according to chemical analyses by Mathews (1951) of Cascade volcanic rocks, that the glass was derived from an acid magma with a silica content of about 72 percent.

The crystals are generally euhedral and relatively free of inclusions. Some of the crystals have thin rims of glass at their margins, but most have been cleanly separated from the glass. Listed in order of abundance the crystals consist of andesine, hypersthene, hornblende, magnetite, and a trace of augite.

The same suite of minerals has been identified in the coarse pumice fragments near Glacier Peak by Gould and also by Carithers (1946).

Samples of ash from alluvium in southern Alberta and northwestern Montana are similar in composition. According to Horberg and Robie (1955), the glass shards range in refractive index from 1.505 to 1.518, and the crystals consist of plagioclase, hornblende, magnetite, enstatite, and biotite. As enstatite and hypersthene belong to the same isomorphous series and are similar petrographically, it is likely that the mineral identified as enstatite by Horberg and Robie corresponds to hypersthene in our samples. Biotite, which was recognized in several samples in Montana and Alberta by Horberg and Robie, does not appear in our samples. However, as the material examined by them was collected from alluvium, it is possible that the biotite is not a primary constituent of the ash but was derived from local sources.

Although the constituents of the 14 ash samples examined are the same, the ratio of crystals to glass and the percentage abundance of the several mineral species show marked and progressive changes (figs. 3-6) as a function

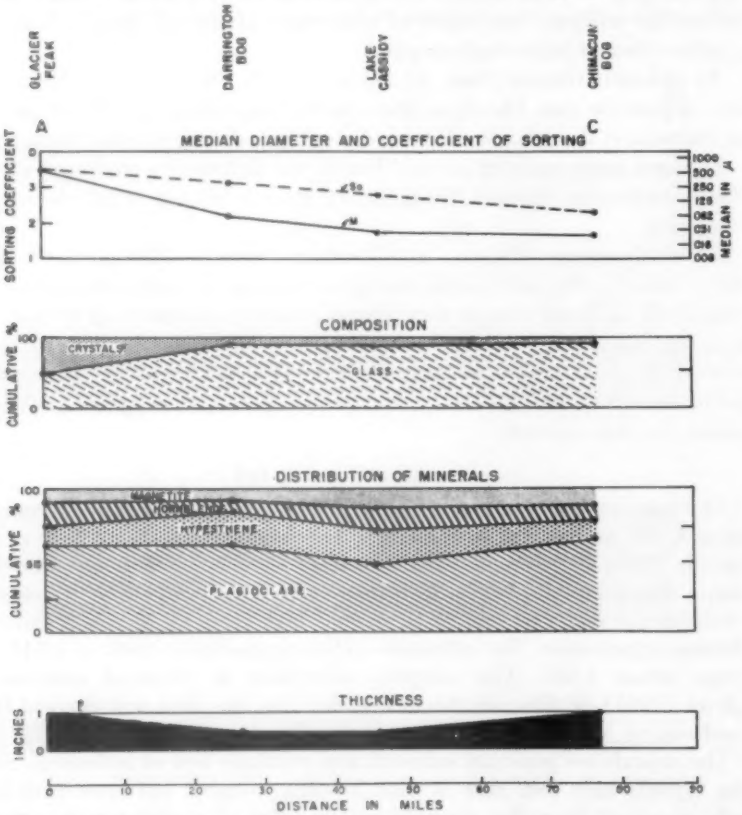

Fig. 4. Section westward from Glacier Peak showing sedimentary and petrographic features of the ash layer.

of the distance from Glacier Peak. At Glacier Peak the ash consists of 50 percent glass and 50 percent crystals. As the distance increases along the four section lines radiating from Glacier Peak, the crystal content with minor exceptions decreases progressively and the glass content increases. For example, in section A-B (fig. 3) the crystal content of the ash in Lake Washington, 63 miles southwest of Glacier Peak, has decreased to 23 percent and at Belmore Bog, 116 miles from Glacier Peak, the crystal content has been reduced to 15 percent. In section A-E (fig. 6) the crystal content at Bailey Lake, 173 miles east of Glacier Peak, has been reduced to 18 percent. Still farther to the east in northwestern Montana and southern Alberta, about 400 miles from Glacier Peak, the average crystal content according to Horberg and Robie (1955) is about 8 percent.

In general, a similar relationship is noted in the proportion of heavy crystals (hypersthene, hornblende, and magnetite) to light crystals (plagioclase). As shown in figures 3 to 6, the heavy minerals with minor exceptions decrease relative to plagioclase with increasing distance from Glacier Peak.

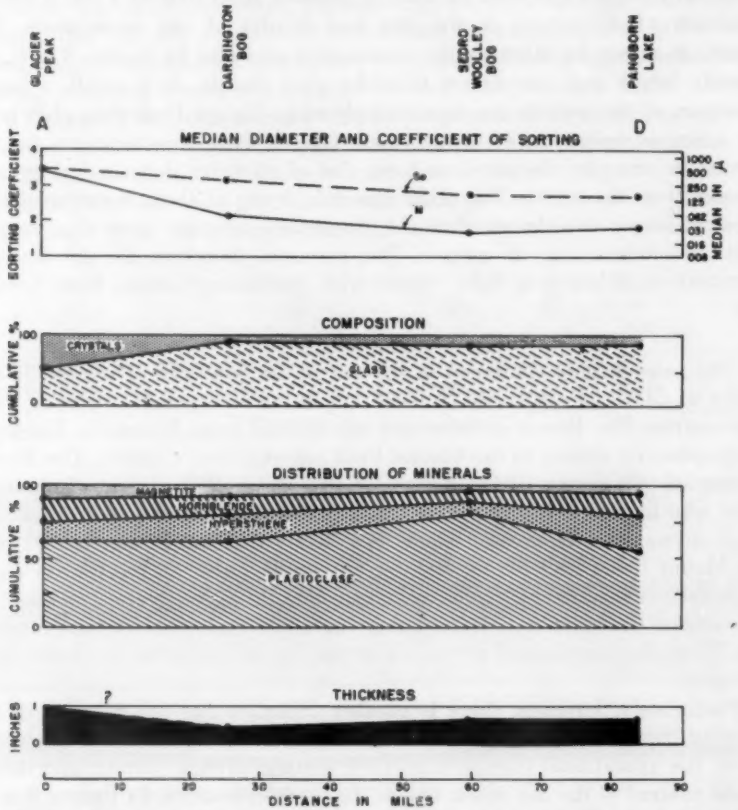

Fig. 5. Section northwest from Glacier Peak showing sedimentary and petrographic features of the ash layer.

This relation is demonstrated nicely in sections A-B (fig. 3) and A-E (fig. 6). In section A-B the heavy minerals range from 38 percent of the total crystal content at Glacier Peak to only 28 percent of the total crystal content at Belmore Bog, 116 miles to the southwest. Eastward from Glacier Peak the decrease in heavy mineral content is even more striking. At Bailey Lake, 173 miles from Glacier Peak, the heavies make up only 20 percent of the total crystal content. Judging from the data of Horberg and Robie (1955), the Montana and Alberta ash shows a further decrease in percentage of heavy minerals.

The local exceptions to these generalizations, which are apparent in a few of the sections, are probably a result of local sorting processes within the lakes and bogs themselves and would probably not appear had examination been made of composites of several samples from each locality rather than of individual samples.

The decrease in proportion of crystals to glass and in proportion of heavy crystals to light crystals with increasing distance from Glacier Peak is clearly a function of differences in the size and density of the constituents. The crystals, as shown by microscopic examination and also by figures 3 to 6, are generally larger and also denser than the glass shards. As a result, a larger proportion of the crystals are deposited closer to Glacier Peak than elsewhere. This selective deposition of crystals near Glacier Peak thus accounts for the decrease in size and the more uniform size of particles deposited at greater distances from the source. The mafic minerals, being of about the same size or somewhat larger and denser than the plagioclase crystals, were deposited in greater abundance near the source. This accounts, therefore, for the decrease in proportion of heavy to light crystals with increasing distance from Glacier Peak.

SOURCE AND AGE OF THE ASH

The petrographic similarity of the ash in the bogs and of the ash in the vicinity of Glacier Peak is not in itself conclusive evidence that Glacier Peak is the source. The Recent pumice and ash ejected from Mount St. Helens is petrographically similar to the Glacier Peak ash (Carithers, 1946). The Mount Mazama ash (Williams, 1942) except for its considerable content of augite is similar also in composition to the pyroclastics erupted from Glacier Peak. Although no analyses have been made, it is likely that the Recent pyroclastics from Mount Baker and Mount Rainier are similar, also, to the Glacier Peak ash. In fact, the similarity of the rocks extruded from the several volcanoes of the northern Cascades is a feature that has impressed all who have studied them. Thus, the composition of the ash in itself is of little value in establishing the source.

Fortunately, however, there is another criterion that can be used in determining the source and in correlating the ash at widely scattered localities; namely, the gradational change in texture, sorting, crystal content, and heavy mineral content of the ash about one of the possible sources. In figures 3 to 6, the progressive decrease in particle size, coefficient of sorting, crystal content, and heavy mineral content about Glacier Peak as a center clearly points to

Glacier Peak as the source. It might be said that the gradational properties of samples of section A-E (fig. 6) eastward from the Cascades could be related to Mount Rainier or Mount Baker as a source just as convincingly as to Glacier Peak. Admittedly this is true, but such a possibility does not exist for the other sections (figs. 3-5). The most critical traverse supporting Glacier Peak as a source is section A-B (fig. 3) which trends southwestward across the Puget Sound Lowland and passes northwest of Mount Rainier and Mount St. Helens at close range. The progressive decrease in size, crystal content, and heavy mineral content of samples along this section, as related to Glacier Peak as a source, does not change with proximity to Mount Rainier and Mount St. Helens which precludes the possibility that the ash could have been derived from either of these volcanoes.

The gradational properties and the distribution of the ash occurrences about Glacier Peak as a center allow no other interpretation but that Glacier Peak is the source. Furthermore, the gradational properties add weight to our previous interpretation that the blast from Glacier Peak, which produced the ash layer, was single and short. Had the eruption been multiple and long, it is unlikely that the ash would have maintained the same textural and mineralogical proportions which are necessary requisites for the progressive horizontal grading observed. Important support for this interpretation is the statement by Williams (1942) that because of multiple eruptions there is no progressive gradation in the texture and crystal content of the Mount Mazama ash.

To obtain the age of the ash layer, 1-inch sections of peat immediately underlying the ash were collected from two bogs for Carbon–14 dating. One of the bogs, Moss Lake Bog, is about 25 miles northeast of Seattle and at an

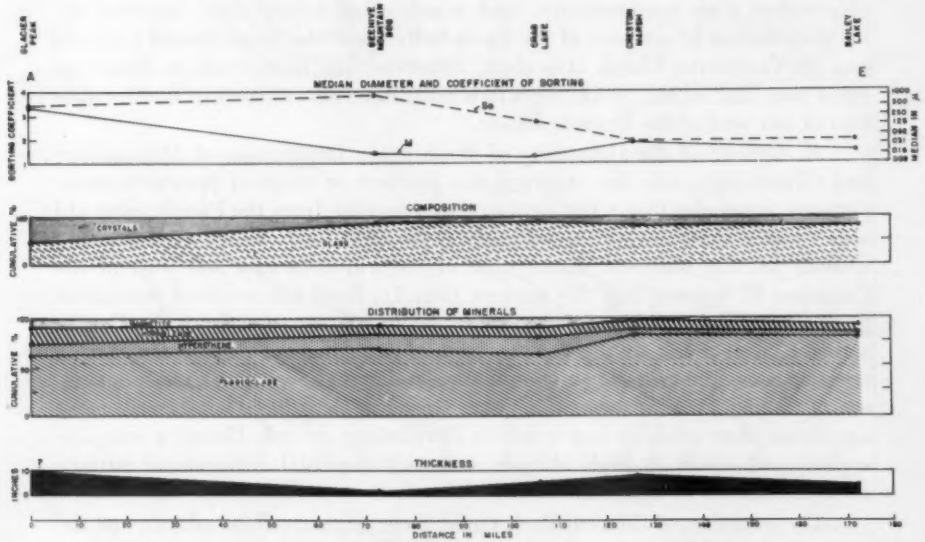

Fig. 6. Section eastward from Glacier Peak showing sedimentary and petrographic features of the ash layer.

altitude of 540 feet; and the other, Covington Bog, is about 25 miles southeast of Seattle and at an altitude of 410 feet (fig. 1). The bogs are approximately 30 miles apart. To obtain sufficient material, between 20 and 30 closely spaced cores were taken for each sample which was a composite from the cores. As all cores contained the ash layer, no difficulty was encountered in correlating the segments used in making up the composite sample. At Moss Lake Bog the ash, which occurs as a 1-inch layer in limnic peat at a depth of 14 feet below the bog surface, was determined at 6,950 ± 200 years, and at Covington Bog, the age of the ash, which occurs as a 1/2-inch layer at a depth of 13.75 feet, was determined at 6,500 ± 200 years. The average of these determinations, which is very nearly within the limit of analysis error, places the age of the ash layer and the eruption of Glacier Peak at about 6,700 years. This is remarkably close to the 6,000-year estimate of Hansen (1947) obtained by older methods.

Although there is little question of the Glacier Peak origin and uniform age of the ash at the localities depicted in figure 1, additional radiocarbon ages of the ash in widely scattered localities, particularly in British Columbia, Alberta, and Montana, should not be discouraged.

A radiocarbon date of 6,500 years (Libby, 1952) for the Mount Mazama eruption in Oregon, which resulted in the formation of Crater Lake, indicates that the period 6,500 to 6,700 years ago was perhaps a time of general volcanic activity in the Cascades of Washington and Oregon.

ATMOSPHERIC CONDITIONS DURING ERUPTION OF GLACIER PEAK

From the widespread distribution and great thickness of the ash northeast of Glacier Peak, it is clear that the prevailing and strongest winds at the time of eruption were southwesterly. Such winds could not account, however, for the distribution of ash west of the Cascade Range in the Puget Sound Lowland and on Vancouver Island. It is clear, therefore, that light winds at directions other than that of the prevailing winds must have participated in the distribution of ash west of the Cascade Range.

R. J. Reed of the University of Washington Department of Meteorology and Climatology, who has analyzed this problem in terms of present weather patterns, concludes that a low pressure area moving from the Pacific eastward over Glacier Peak during the eruption is the most likely situation that would account for the observed distribution of the ash both east and west of the Cascades. In constructing this pattern (fig. 7), Reed has assumed that about three days were required for the atmospheric low to travel from the Pacific across Glacier Peak to the eastern part of Washington. As the ash during eruption was doubtless blown several thousand feet above the 10,528-foot summit of Glacier Peak, it seems likely that strong, high altitude winds were more significant than weak surface winds in distributing the ash. Hence, a complete sequence of winds at high altitude and only a partial sequence of surface winds are shown in figure 7.

The eruption of Glacier Peak could have begun well in advance of the appearance of the low pressure area off the Washington coast and the ejecta carried to the northeast by steady southwesterly winds. With the appearance

of the low pressure area off the coast (fig. 7A), however, the winds in the vicinity of Glacier Peak would have changed to west-northwesterly, and the ash would have been carried eastward toward Spokane. As the low proceeded

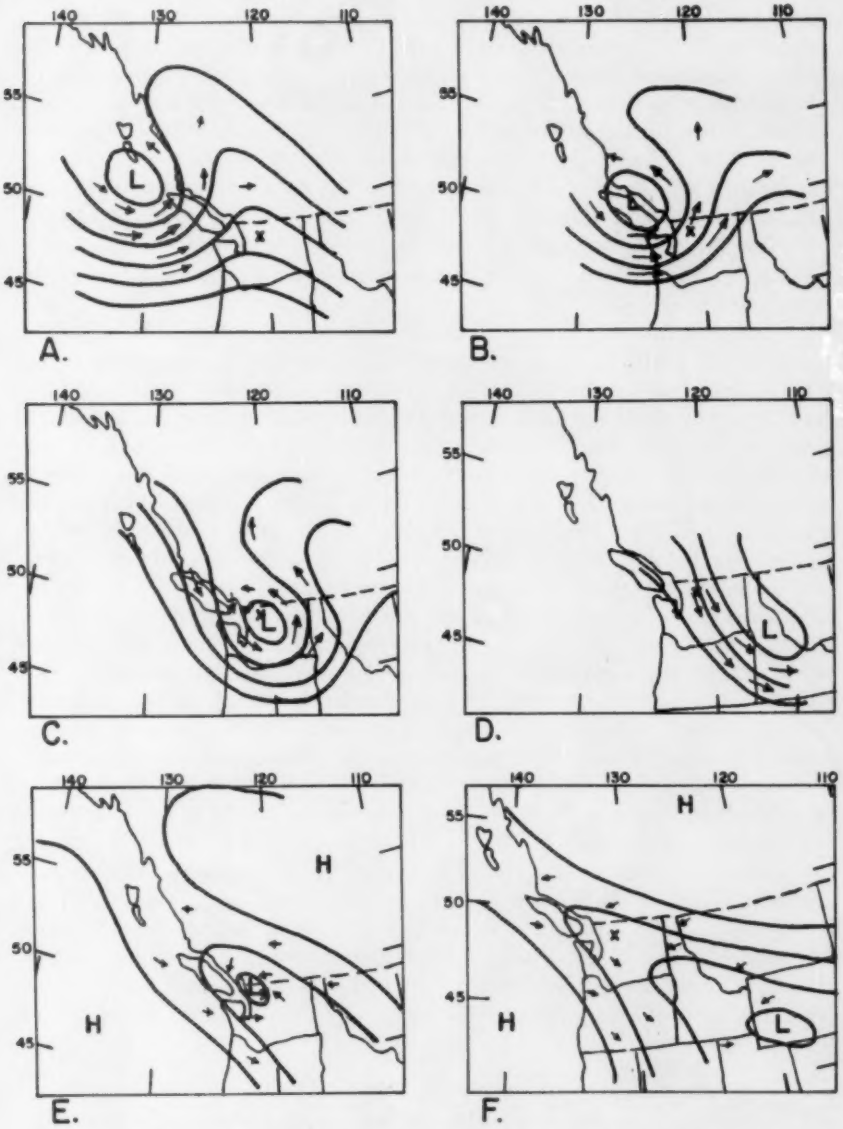

Fig. 7. Sequence of winds accompanying movement of low pressure area eastward across Glacier Peak. Diagrams A to D show high altitude winds at 20,000 feet. Diagrams E and F show surface winds corresponding respectively to high altitude winds in diagrams B and D. Location of Glacier Peak denoted by "x".

in over the coast (fig. 7B), the flow of air over Glacier Peak would have shifted back again to north-northeast. In figure 7C, with the low centered over Glacier Peak, the ash would have been carried into the Puget Sound Lowland by weak easterly and southeasterly winds. Finally, with progression of the low into Idaho (fig. 7D) the winds about Glacier Peak would have changed to northwesterly and then to southwesterly to complete the sequence. The low altitude or surface winds corresponding to the high altitude pattern of figure 7B are shown in figure 7E, and the surface winds corresponding to the high altitude pattern of figure 7D appear in figure 7F. According to these patterns, volcanic ash falling from the higher strata into the lower strata would be carried by surface winds westward over Vancouver Island and southwestward into the Puget Sound Lowland.

The sequence just described has its greatest frequency of occurrence in the Pacific Northwest in late winter and spring, but it can and does occur in other seasons as well.

From sedimentary and petrographic evidence, it is abundantly clear that the eruption of Glacier Peak was single and short. Just how short, we do not know. It may have endured for only a few days or possibly for a few weeks. Had the eruption lasted only a few days, the observed distribution of ash could be explained entirely by the passage of a single low pressure area over or near Glacier Peak. However, to account for the great thickness of ash to the northeast, this would require that a much greater volume of material was ejected from Glacier Peak at the beginning of the eruption when southwest winds prevailed than at the end of the eruption when the winds were easterly and southeasterly. On the other hand, had the eruption lasted a few weeks, the great thickness of ash to the northeast could have been laid down by strong southwesterly winds blowing for some considerable time before and/or after the arrival of the atmospheric low off the coast. As the low continued over Glacier Peak, the winds would have been diverted to easterly and southeasterly for only a brief period and would have deposited only a thin layer of ash west of the Cascades. Of these two possibilities, the latter appears more plausible because it requires no coincidence of eruption with a low pressure area of short duration nor does it require a variable rate of supply of ash to coincide with specific wind directions.

From the sequence of winds proposed by Reed, it is quite pobable that ash from Glacier Peak was carried and deposited south of the southern limit of ash distribution depicted in figure 1. This is suggested, also, by the considerable thickness of ash in some of the bogs near Spokane along the southern boundary of the area of known ash distribution. It seems quite likely, therefore, that further exploration to the south will extend the limits of ash of Glacier Peak origin.

AGE OF RECESSION OF VASHON ICE FROM WESTERN WASHINGTON

To determine the age of basal peat at the sampling localities in Moss Lake Bog and Covington Bog (fig. 1), 1- to 3-inch sections of limnic peat immediately overlying the glacial meltwater sediments in the bottoms of the bogs were collected for radiocarbon dating. At Moss Lake Bog, the age of the basal

peat immediately overlying glacial blue clay at a depth of 22.75 feet below the bog surface is 11,900 ± 360 years, and at Covington Bog, the age of the basal peat overlying Vashon outwash sand and gravel at a depth of 54.5 feet below the bog surface is 10,200 ± 500 years.

During the course of field work, we presumed that the basal peat sampled probably had been deposited shortly after the withdrawal of Vashon ice from these localities and that the ages of the basal peat would correspond closely to the times of ice withdrawal. Subsequent collection and dating of basal peat from Lake Washington, a deep post-glacial lake midway between Covington Bog and Moss Lake Bog, show, however, that the Vashon ice must have receded from these localities considerably before the basal peat at the sampling sites was deposited. Thus, the ages of the basal peat samples from Moss Lake Bog and Covington Bog provide only minimum dates for the recession of Vashon ice from these localities.

In Lake Washington, more than 30 long cores and borings (Gould and Budinger, in preparation) reveal in the deepest part of the lake a sedimentary sequence consisting of 40 feet of limnic peat underlain by blue clay of glacial meltwater origin more than 100 feet thick. Although the post-glacial sediments were penetrated to a depth of 150 feet below the lake bottom (320 feet below mean sea level), the base of the blue clay section was not reached. Within the blue clay and about 10 feet below the blue clay-limnic peat contact is a layer of marine shells. The absence of marine organisms in the clay strata both above and below the marine shell layer suggest that they were deposited in fresh water. Briefly, the Lake Washington sediments record the following post-glacial events:

1. Deposition of the basal blue clay in an ice-margin lake following the retreat of Vashon ice from the Lake Washington basin.
2. Subsequent clearing of ice from the Strait of Juan de Fuca, which allowed invasion by marine waters of the Lake Washington basin and Puget Sound to which the lake basin was freely connected. This event is recorded by the marine shell layer in the blue clay.
3. Conversion of the Lake Washington basin from an arm of Puget Sound to a fresh-water lake represented by the transition from marine clays to fresh-water clays in the upper part of the blue clay section. Isolation of the Lake Washington basin from Puget Sound resulted from damming of the basin at its southern end by delta building.
4. Cessation of meltwater deposition and the beginning of predominantly organic sedimentation in the lake as represented by the transition from blue clay to limnic peat.
5. Continued organic deposition to the present time.

Radiocarbon dating of a sample of basal peat from the blue clay-peat contact places its age at 13,650 ± 550 years. Analysis of a sample from the underlying shell bed, which will date the time of occupancy of the Lake Washington basin by marine water, is still in progress; the results will be presented in a later paper (Gould and Budinger, in preparation).

It is apparent from the above data that some considerable time must have elapsed between the retreat of Vashon ice from the Lake Washington basin and

the deposition of the basal layer of limnic peat. Thus, the 13,650-year age of the basal peat gives only a minimum age for the withdrawal of Vashon ice from the Lake Washington basin.

The Vashon ice sheet at Covington Bog must have retreated from that locality before Lake Washington was freed of ice. It is inconceivable that a relatively thin cover of ice 18 miles south of Lake Washington could have remained in the topographically higher Covington region while a thick sheet of ice extending more than 320 feet below sea level melted from the Lake Washington basin. The 10,200-year age of basal peat at Covington Bog evidently does not correspond, therefore, to the withdrawal of Vashon ice from that locality. Furthermore, it is doubtful that the 11,900-year age of basal peat from Moss Lake Bog dates the retreat of Vashon ice from that vicinity. Although Moss Lake Bog lies a few miles north of the latitude of Lake Washington, it is unlikely that a relatively thin cover of ice could have remained in that topographically higher area more than 1,500 years after the Lake Washington basin was cleared of ice.

According to these determinations, the retreat of Vashon ice from west-central Washington began more than 13,650 years ago. The time elapsed between withdrawal of the ice and this date is unknown. We do know, however, that there was sufficient elapsed time for invasion by marine waters of the ice-front lake in the Lake Washington basin, subsequent conversion of this arm of the sea to a fresh-water lake, and deposition of blue clay more than 100 feet thick in Lake Washington before the basal peat dated at 13,650 years was deposited.

Because this date supplies only a minimum age for the Vashon recession in west-central Washington, we can conclude only that the Vashon is pre-Mankato in age. Mankato glaciation in western Washington was restricted to valley glaciation, the main lobe of which advanced down the Lower Frazer Valley of British Columbia and terminated a few miles south of the Canada-United States boundary (Armstrong, 1956). As reported by Armstrong, a radiocarbon analysis of wood from the base of till deposited by this lobe dates the Mankato advance at 11,300 $\pm$ 300 years ago. Presumably, the Vashon ice sheet retreated from western Washington immediately prior to the Mankato advance, but precise assignment of the Vashon to one of the pre-Mankato substages of the Wisconsin glaciation recognized elsewhere (Horberg, 1955) must await the results of further radiocarbon dating in the Puget Sound area.

As pointed out in the preceding paragraphs, the basal peat sampled in Covington and Moss Lake Bogs post-dates by some considerable interval the withdrawal of the Vashon ice sheet from these localities. There appear to be three possibilities for this time elapse: (1) contamination of the samples by younger overlying sediments during collection; (2) the bogs may be the sites of buried ice blocks which melted out long after the disappearance of surface ice and thus delayed organic deposition; and (3) failure to date the earliest formed organic matter in the bogs. Although the first possibility cannot be evaluated, it is doubtful that any significant contamination of the samples occurred. In support of this view is the close correspondence in radiocarbon

dates of peat samples immediately underlying the volcanic ash layer in Covington and Moss Lake Bogs.

The other two possibilities are likewise difficult to evaluate. Covington and Moss Lake Bogs may well have been the sites of buried ice blocks, but it is doubtful that these would have persisted and prevented organic sedimentation for a few thousands of years after a much thicker accumulation of ice had melted from the Lake Washington basin. On the other hand, failure to date the earliest formed organic matter in bogs can account for very appreciable apparent lags in organic sedimentation. As noted by Deevey (1951), the earliest organic material deposited in many bogs following deglaciation is greatly diluted by inorganic sediments, presumably of meltwater or slope wash origin, accumulating at the same time. He has shown further by pollen studies that the time required for deposition of these sediments low in organic content may be appreciable. Owing to low organic content, the meltwater sediments underlying the basal peat of Covington and Moss Lake Bogs could not be dated by radiocarbon methods. The time required for their deposition may be appreciable, as noted elsewhere by Deevey, and this would certainly account in part for the time lapse between deglaciation and deposition of the basal peat dated in Covington and Moss Lake Bogs.

It has been noted further by Potzger (1956) that the oldest peat deposits in most bogs are deposited in deep central areas and that boring in other localities commonly leads to truncated sections. As the authors were well aware of this feature of bog sedimentation, borings in both Covington and Moss Lake Bogs, obtained previously by Rigg, were used in locating the deepest known parts of these bogs. As noted previously, the basal peat sample at Covington Bog was obtained from a depth of 54.5 feet. Subsequent boring in Covington Bog revealed, however, a maximum depth of 63 feet (fig. 2) in another locality, and it is possible that still greater undetected depths exist. The basal peat sample at Moss Lake Bog was obtained from a depth of 22.75 feet, but here again it is probable that greater unknown depths are present. Accordingly, there is the possibility that the basal peat sampled was not the earliest peat deposited in the bogs. If so, this would account in part for the apparent time lapse in organic deposition. Apparently all of the factors considered have contributed in some degree to lapse between deglaciation and deposition of the basal peat dated by radiocarbon methods. Of these, however, the most significant probably is failure to date the earliest formed organic matter.

In establishing the post-glacial chronology of the Pacific Northwest, Hansen (1947) estimated the time elapsed since the retreat of Vashon ice from western Washington at 18,000 years, and he used this value for the average age of the bog sediments resting on glacial drift or its chronological equivalent. According to the Carbon–14 analysis of the basal peat in Moss Lake Bog, Covington Bog, and Lake Washington, however, the average age of the organic sediments resting on Vashon drift at these localities is about 11,900 years. This value is probably much closer to the average age of all bog sediments resting on Vashon drift in western Washington than the 18,000-year estimate of Hansen. Accordingly, the average of the Carbon–14 dates, 11900 years,

places the chronology of post-glacial events in western Washington on a more precise basis than was previously possible.

RATE OF PEAT SEDIMENTATION AND POST-GLACIAL CHRONOLOGY

The thickness of organic sediments accumulated in the bogs since the withdrawal of the Vashon ice sheet ranges within wide limits. Of 151 bogs bored in the Puget Sound Lowland, the maximum thickness of peat deposited ranges from 4 to 63 feet and averages 24 feet as determined from the deepest borings in each bog. As organic sediments in most bogs accumulate more rapidly in the deep central areas rather than at the shallow margins, there is a similar wide range in the thickness of organic sediments in individual bogs (fig. 2). Because of this great variability, averages of the thickness of organic sediments and of rates of sedimentation must be used with caution. However, as Hansen (1947) has stated, the more numerous the profiles from a homogeneous geomorphic and climatic province, the more significant the averages of thicknesses and rates of organic sedimentation become.

To obtain such averages, the deepest borings in 206 bogs from Washington and surrounding areas were analyzed. Of these, 151 are from the Puget Sound Lowland and 55 are from other areas including the Columbia Plateau, northeastern Washington, Idaho, and British Columbia. For each of these groups, the total thickness of organic sediment, the thickness of peat above and below the ash layer, and the thickness of limnic and fibrous peat were measured. For convenience and simplification, the sphagnum and fibrous peat were grouped together as fibrous peat. The results of these determinations (table 1) show that for all 206 bogs, the peat averages 22.6 feet in thickness and consists of 10.1 feet of limnic peat overlain by 12.5 feet of fibrous peat. The ash layer lies at an average depth of 13.4 feet and is overlain by 0.9 foot of limnic peat and 12.5 feet of fibrous peat. These values correspond closely to the averages obtained by Hansen (1947) from 30 profiles of bogs in the same general area which show 22.6 feet of organic sediment consisting of 11.1 feet of limnic peat and 11.5 feet of fibrous peat. The mean depth of the ash layer according to his determinations is 14.4 feet.

The average thickness of organic sediments (24.0 feet) in the Puget Sound bogs is about five feet greater than the average thickness (18.8 feet) of organic sediments in other areas, and the mean depth of the ash layer (14.1 feet) in Puget Sound bogs is about 2.5 feet greater than in bogs outside the Puget Sound Lowland. These differences in thickness and in depth of the ash layer result from a more rapid rate of peat accumulation in the Puget Sound area owing to prolific plant growth afforded by more favorable climatic conditions.

From these averages of sediment thickness and the Carbon–14 ages of the ash layer and of the basal peat at the bottoms of the bogs, average rates of peat sedimentation can be readily computed. In the Puget Sound Lowland where all the bogs analyzed lie on Vashon drift, it is assumed that the age of the basal peat is 11,900 years, the average of three radiocarbon analyses. As no Carbon–14 determinations are available of the peat at the bottoms of bogs in other areas of this study, no attempt has been made to determine the

TABLE 1
Average Thickness of Peat and Mean Rates of Peat Sedimentation in Bogs of Washington and Surrounding Areas

Area	Thickness of peat in feet					Rate of sedimentation in years per inch		
	Total column	Above ash	Below ash	Limnic peat	Fibrous peat	Total column	Above ash	Below ash
Puget Sound Bogs (151)*	24.0	14.1	9.9	10.6	13.4	41.0	39.6	43.0
Bogs outside Puget Sound (55)*	18.8	11.5	7.3	8.6	10.2	—	48.5	—
All bogs (206)*	22.6	13.4	9.2	10.1	12.5	—	41.7	—

* Figures in parentheses indicate number of bogs used in the determination of averages.

average rates of sedimentation of peat in the lower parts of these bogs. However, the rates of sedimentation of peat above the ash layer in these bogs as well as in those in the Puget Sound area can be computed from the 6,700-year radiocarbon age of the ash layer.

The results of these determinations (table 1) show that in the Puget Sound Lowland the average rate of post-glacial peat sedimentation has been 41.0 years per inch and that the rate of accumulation (43.0 years per inch) prior to the ash fall was slightly less than the rate of accumulation (39.6 years per inch) since the ash fall. In areas outside of Puget Sound, the average rate of peat sedimentation since the deposition of the ash layer has been 48.5 years per inch. In 120 bogs in Washington where the ash layer is overlain entirely by fibrous peat, and in 67 bogs of the Puget Sound area where the ash is underlain entirely by limnic peat, it has been possible to determine the rates of deposition of fibrous and limnic peat independently. According to these calculations, the average rate of sedimentation for fibrous peat is 68.1 years per inch and for limnic peat is 47.8 years per inch. From inspection of table 1 it is clear, however, that this low rate of fibrous peat accumulation does not apply generally to all of the bogs, and the average rates of fibrous and limnic peat sedimentation based on all sections must be about equal.

Perhaps the most striking result of this analysis is the equality in sedimentation rate above and below the ash layer and the general correspondence between the rates of deposition of limnic and fibrous peat. Most investigators have considered that limnic peat accumulates much more slowly than fibrous

peat. In fact, Hansen (1947), in constructing his post-glacial chronology of climates and forests in the Pacific Northwest, assumed that limnic peat accumulated only one-half as rapidly as fibrous peat. Had he used his 6,000-year estimate for the age of the ash layer as a prime chronological reference and assumed the same rate of sedimentation for fibrous and limnic peat, he would have obtained an age for the basal peat which would correspond closely to our 11,900-year radiocarbon average.

CONCLUSION

Owing to the widespread distribution, distinctive character, and short time represented by the Glacier Peak ash, it fulfills the requirements of a key bed in the Recent sediments of Washington and adjacent areas. The 6,700-year radiocarbon age of the ash layer is particularly significant because it serves as a prime reference for establishing an absolute chronology of post-glacial events in an area of approximately 180,000 square miles.

The 13,650-year radiocarbon age of basal peat in Lake Washington establishes this as a minimum date for withdrawal of the Vashon ice sheet from west-central Washington. Thus, the Vashon glaciation is pre-Mankato in age. The radiocarbon dates of basal peat in Covington Bog and Moss Lake Bog serve as additional absolute chronological references. Further age determinations of basal peat in other bogs and lakes, which will extend this chronology, should be encouraged.

The methods used in correlation of the ash, in recognizing the singleness and shortness of the eruption that produced it, and in identifying Glacier Peak as the source have been employed successfully in tracing the ash from similar eruptions of active volcanoes in Java and surrounding areas (Mohr and Van Baren, 1954; Kuenen and Neeb, 1943). Application of these methods to additional ash layers prominent locally in the vicinity of other volcanoes of the Washington Cascades appears to be a promising approach to the problem of correlating these beds.

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ON THE SIGMOID GROWTH PHASE IN THE HISTORY OF LINSLEY POND

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ABSTRACT. Some new calculations are presented involving previously published data from Lower Linsley Pond.

Using the brown bands of Vallentyne and Swabey as a time scale, the *Bosmina* counts and organic-inorganic measurements of Deevey have been translated into terms of sedimentation per square centimeter per year. Recalculated in this way the results show that the apparent logarithmic increase in *Bosmina* production early in the history of the lake is valid, but that the logarithmic increase in organic matter is very largely an artifact due to the previous methods of calculation. The most significant change during this period was a decrease in the rate of inorganic sedimentation.

It is suggested that silting controlled the production of *Bosmina* and other plankton organisms in the early history of the lake, and again in recent years, by interfering with the regeneration of nutrients in the diagenetic layer. This suggestion is supported by the close correspondence between the ratio of phosphorous to total organic matter, calculated from the data of Hutchinson and Wollack, and the ash content of the sediment.

INTRODUCTION

The principal change in the stratigraphy of Lower Linsley Pond in North Branford, Connecticut, is a sigmoid increase in the organic and microfossil content of the sediment which has been attributed to an internal change in the productivity of the ecosystem (Hutchinson and Wollack, 1940; Deevey, 1942). This commentary will show that the sigmoid increase is associated with extralacustrine changes and may be the result of the world-wide postglacial warming.

In a recent publication dealing with the sedimentary history of Linsley Pond, Vallentyne and Swabey (1955) presented a regression line for the thickness with increasing depth of a series of brown bands found near the bottom of the lake deposit. Correlating from the radiocarbon-dated sediments of Upper Linsley Pond one age estimate was obtained for a level in the banded gyttja and another for a level not far above the top of the band series. By extrapolating the regression line to the upper level of measured age they arrived at an estimate of the rate of band formation of 2.65 bands per year. A second computation, based on the regression line for only the bands lying between the carbon-dated levels, gave a figure of 2.42 bands per year.

If, as seems probable, these bands were formed at a constant rate, they must reflect some event which occurred two or three times each year. No major event is known to occur three times each year in lakes, but the breakdown of stratification and complete overturn of the water does occur twice annually in many lakes, including Linsley Pond. Considering the amount of correlation and extrapolation involved in obtaining the figures of 2.42 and 2.65 it seems likely that the bands were laid down at the rate of two per year and that they represent some aspect of the equinoctial overturn, possibly the diatom maxima which are produced in many lakes just after each complete circulation.

In the discussion that follows it is assumed that the brown bands were laid down at the rate of two per year and they are used to establish a chronology that is absolute, though floating. For most purposes it would be just as

useful to assume that any particular number of bands had been laid down each year, but it is essential to the argument that the bands should have been deposited at a constant rate.

The history of Linsley Pond has been under investigation for many years by a number of investigators (Hutchinson and Wollack, 1940; Deevey, 1942; Patrick, 1943; Vallentyne and Swabey, 1955) and many important conclusions have emerged from their work. One of the most interesting results has been the discovery of a flexion in the curves of such measures of past productivity as *Bosmina* abundance, organic content and chlorophyll content (fig. 1) which indicates that the biocoenosis of the lake passed through a

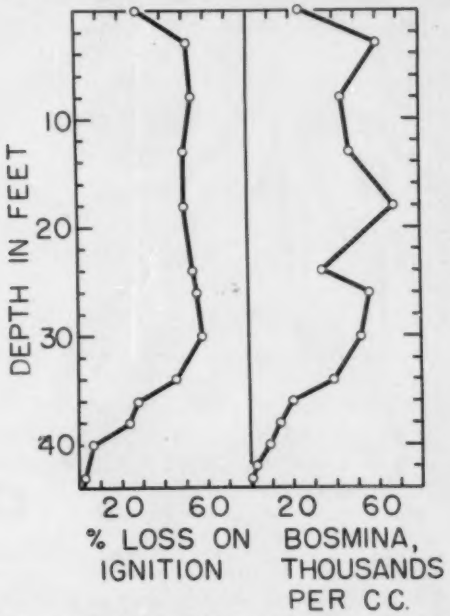

Fig. 1. Percent loss on ignition and *Bosmina* content of wet sediment, from Deevey (1942).

phase of logarithmic growth early in its history. Unfortunately the absence of an absolute chronology has forced the investigators to assume in their calculations that the rate of sedimentation did not vary greatly during the interval under investigation. On that basis the weight of the published evidence suggests that the growth of the biocoenosis has been similar to that of an individual or a population, even though, as Vallentyne and Swabey state, "The factors controlling the sigmoid growth have yet to be elucidated." This note attempts to elucidate these factors.

ACKNOWLEDGMENTS

The ideas expressed here are the outcome of many long discussions, particularly with Dr. J. R. Vallentyne of Queens University, Dr. E. S. Deevey and Prof. G. E. Hutchinson of Yale and Dr. F. R. Hayes of Dalhousie. Although

these gentlemen are in no way responsible for such errors as may be present in this theoretical treatment they have contributed at least as much as the author to the development of it.

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SEDIMENTATION RATES

By accepting the Vallentyne-Swabey regression line and applying it to the data of the earlier authors it is possible to convert all their measures of microfossils and chemical constituents from quantities per unit volume of sediment to quantities preserved per unit area per year. This has been done for a few selected items and the results are plotted in figure 2.

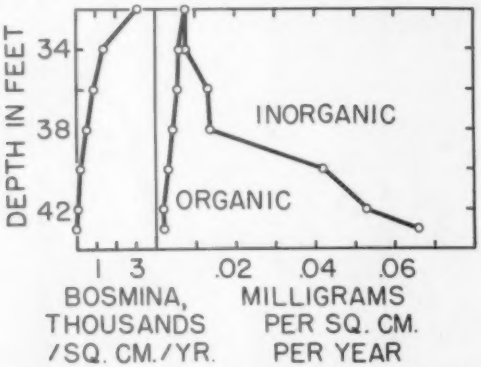

Fig. 2. *Bosmina* carapaces, organic matter and inorganic matter per square centimeter per year, calculated from the data of Deevey (1942) and Vallentyne and Swabey (1955) on the assumption that the rate of band formation was constant at two per year.

This calculation is based on results from two different cores, L-10 of Deevey and LV of Vallentyne and Swabey, and so depends on a correlation between them. The points which were used for correlation were the base of pollen zone C-1 and the beginning of the sharp increase in ignition loss, which lie near opposite ends of the banded zone in core LV. In LV the base of pollen zone C-1 is 10.75 meters below the mud surface, in L-10 about 10.4 meters. In LV the rapid rise in ignition loss begins about 13.5 meters below the mud surface, in L-10 about 12.8 meters. Because of this rather close correspondence the two cores have been correlated meter for meter from the mud surface. Band thickness does not change very rapidly through the banded zone so the errors introduced into the calculation will not be serious.

The first result of this calculation is confirmation of the current belief that zooplankton productivity, as measured by *Bosmina* fossils, has gone through a phase of logarithmic increase.

The second result is that the organic matter preserved per year has increased, but only slightly. The greater part of the spectacular flexion in the loss-on-ignition curve is due to a sharp decline in the rate of inorganic sedi-

mentation. Hutchinson and Wollack suggested the possibility of a very high rate of inorganic sedimentation early in postglacial time and some unpublished observations by the author indicate that there is much silting in arctic lakes. Deevey (1939) and Deevey and Potzger (1951) have presented pollen evidence to show that the Connecticut climate during the early history of Linsley Pond was much colder than it is now, perhaps subarctic, so it is not surprising that a great change in the rate of inorganic sedimentation has occurred since the lake was formed.

PHOSPHORUS REGENERATION AND CHANGES IN PRODUCTIVITY

The significance of the change in annual sedimentation of inorganic matter lies in the fact that it shows quite clearly that the sigmoid phase of growth occurred while external influence upon the ecosystem was changing greatly. It seems likely that the sigmoid increase is the result of this external change, and one immediately seeks a mechanism whereby the change in mineral sedimentation could have affected the development of the biocoenosis.

The most direct way in which silting could influence the size of the biomass would be by physical interference with the organisms in the water. Much mineral matter suspended in the water would shade the phytoplankton and might interfere with the filtering and respiratory apparatus of the animals. The actual amount of inorganic material deposited, however, was less than 0.07 milligrams per square centimeter per year, an amount that would hardly be noticeable if suspended in water.

It is quite probable that the high ash content acted by interfering with the release of nutrients from the mud surface. It has been known for a long time (Hutchinson and Wollack, 1940) and emphasized by recent tracer studies (Hayes, McCarter, Cameron and Livingstone, 1953) that a very large part of the mass of nutrient material in a fresh-water ecosystem is derived from the mud. Anything affecting the state or composition of the mud would be in a particularly good position to influence the productivity of the lake.

Experimental studies by Cameron (1951) and Hayes (1955) have shown that the actual thickness of mud concerned in the exchange of phosphorus with the water is quite small—almost certainly less than a single centimeter. Under these circumstances it might be possible for the silt to cut down by simple dilution the amount of phosphorus released. If only the upper centimeter regenerates phosphorus, then a lake bottom composed of equal volumes of silt and gyttja would release no more than half as much phosphorus as one consisting of pure gyttja. Such simple dilution, however, is not enough to explain the phenomenon of biomass growth in this case. Although the ash content falls rapidly through the banded zone the water content rises and the net result is only a minor decrease in the thickness of annual deposit over the banded zone.

The effect of ash, however, cannot be one of simple dilution. Even if the process of phosphorus release were a purely physical one mineral grains would have a much greater effect than an equal volume of water on the rate of diffusion of phosphorus from the mud. As it is almost certainly a biochemical and bacteriological process, the inhibiting influence of ash on phosphorus

release would be even greater—perhaps great enough to prevent more than a small fraction of the mud phosphorus from being released before it was buried beneath the zone of diagenesis and removed from the economy of the lake forever. Indeed, it is to be expected that the mineral matter would interfere by processes of adsorption and ion-exchange with phosphorus release from the mud.

These are questions which are capable of direct experimental investigation and it is hoped that actual figures for the influence of inorganic matter upon the rate of phosphorus release at the mud-water interface will be forthcoming as a result of studies now being carried on at Dalhousie University. In the meantime we are forced to rely on the analysis of Linsley Pond data. If less phosphorus were released from the sediments when the ash content was high, then, provided that the ratio of phosphorus to organic matter in the sediment rain has been constant, we should find relatively more phosphorus in the mineral sediment than in the organic gyttja. This is precisely the result which emerges from the chemical analyses of Hutchinson and Wollack (1940), as can be seen from the curves of figure 3.

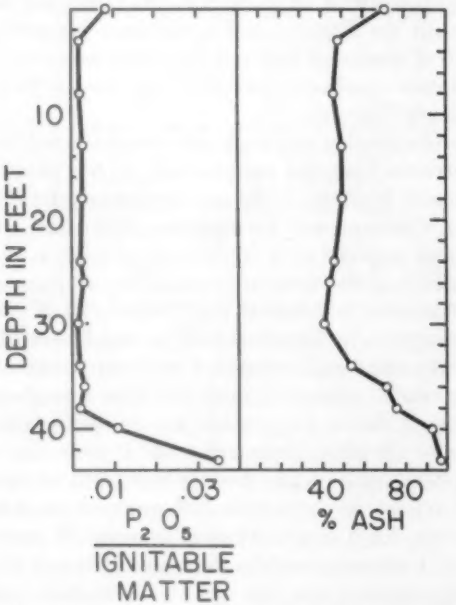

Fig. 3. Ratio of P_2O_5 to ignitable matter, calculated from the data of Hutchinson and Wollack (1940) and non-ignitable matter, replotted from Deevey (1942).

It may be of some interest to examine the bottom part of the banded zone, where the phosphorus content of the sediment is decreasing and the *Bosmina* content increasing, to see if, on the basis of increasing diagenetic efficiency, there is sufficient change in phosphorus to account for the increase in *Bosmina*.

First, let us assume that the rate of delivery of phosphorus to the sediments has not changed and that the variations in the phosphorus content of the sediment are due to variations in the rate of regeneration to the water after deposition. From the phosphorus data of Hutchinson and Wollack and the band measurements of Vallentyne and Swabey it is possible to calculate the P_2O_5 content per square centimeter per band for five levels in the banded zone:

Depth in feet	Mgms. P_2O_5/cm.^{2}/band
34	0.0135
36	.0173
38	.0104
40	.0370
43	.0713
Mean	0.0394

The mean value is 0.0394 milligrams per square centimeter per band. Summed over 8640 bands, the approximate number between the 34- and 43-foot levels, this gives a total of 340 milligrams of P_2O_5. If all the sediment were as rich as the 43-foot level this figure would be 616 milligrams, so there is a difference of 276 milligrams of P_2O_5, which, on the theory of a change in diagenetic efficiency, is the extra amount of this nutrient released from the mud by increased diagenesis and available to support the increased *Bosmina* production.

Assuming that the water level stood where it does today the amount of water over each square centimeter of the bottom surface in the place where these cores were taken was about 2.6 liters; 276 milligrams of phosphorus would provide 106 milligrams per liter.

The present high *Bosmina* productivity of Linsley Pond is sustained by a total water phosphorus content (dissolved + particulate) of 0.021 milligrams per liter (Deevey, 1940). Assuming that ten times this amount is actually present in the system, in the bodies of fish, benthos and rooted aquatic plants, we find 0.21 milligrams per liter quite adequate to explain the increase in *Bosmina* during the early history of the lake. Our postulated phosphorus source is more than adequate by a factor of 500.

This discrepancy is not surprising, for the calculations neglect the amount of phosphorus lost through the outlet stream during 4000 years. The lack of adequate quantitative data on this loss and also the possibility that the rate of delivery of phosphorus to the lake may have changed make the computation of much less value than it would otherwise be. All that can be said is that the hypothesis of changing diagenetic efficiency provides a potential supply of phosphate more than sufficient to account for the increase in *Bosmina* production. How much of the potential supply was actually used in this way cannot be determined.

CONCENTRATION OF BOSMINA REMAINS

Deevey (1942) found that there was an allometric relationship between the *Bosmina* content and the organic matter content of the sediment during

the phase of growth. Taking the organic mater as a measure of the size of the total biomass, then a part of the biocenosis, *Bosmina*, was growing faster than the biocoenosis as a whole. When the data are plotted in terms of bands instead of cubic centimeters the same result, of course, holds.

The hypothesis of changing diagenetic efficiency provides a possible explanation for the allometry. *Bosmina* carapaces are very resistant to decomposition in a lake-mud environment as is attested by their well-nigh universal occurrence as fossils in the sediments of freshwater lakes. An increase in diagenetic efficiency would remove other things preferentially, leaving a lag-concentrate of *Bosmina* remains. Let us see how great a change in the amount of diagenesis would be necessary to account for the observed allometry.

At 42 feet each band contains 60 *Bosmina* carapaces and 2.2 milligrams of organic matter per square centimeter; at 32 feet each band contains 3080 carapaces and 7.5 milligrams of organic matter. If we assume that there has been no change in the relative production of *Bosmina* and organic matter (the opposite of Deevey's assumption) and that the conditions at 42 feet represent a minimal amount of diagenesis, then

60 *Bosmina* originated in 2.2 mgm. organic matter

1 *Bosmina* originated in 2.2/60 mgm. organic matter

3080 *Bosmina* originated in 3080 x 2.2/60 mgm. = 113 mgm. organic matter

Of this amount, only 7.5 milligrams remain at 32 feet, so about 105 milligrams more organic matter must have been lost by diagenesis than at the 42 foot level, if we are to explain the allometry on this basis.

This requires a rather large amount of organic decomposition and hence of organic production. Riley (1940), using light and dark bottle experiments, has estimated the present productivity of Linsley Pond at 1.20 $\pm$ 0.20 milligrams per liter per week. This gives a figure of 52 x 1.20 x 1.5 = 93.6 $\pm$ 15.6 milligrams per year for the amount of water over one square centimeter of bottom in the deep part of the present lake. We may take this figure as an estimate of the annual production during deposition of the banded zone. If the productivity during the weeks when Riley carried out his experiments was higher than the annual average during the time we are considering, as seems quite possible on several grounds, this estimate will be too high. Even if accurate it indicates that the organic production of Linsley Pond was probably somewhat less than is required to explain the allometric relationship between *Bosmina* fossils and organic matter on this basis.

The phenomenon of allometry is not completely and satisfactorily explained by changes in diagenetic efficiency but it is evident that they will go a long way toward explaining it. In any case diagenesis must be taken into account. It is a simpler and more tangible, if less interesting, process than the changes in trophic structure of the developing ecosystem implied by the original explanation of allometric growth.

RATE OF BAND FORMATION

So far we have assumed a constant rate of formation of the brown bands. If the bands have been formed at an inconstant rate the argument will be seriously impaired, and it may be interesting to see just how much it will suffer from a reasonable amount of change in the rate of band formation.

Earlier in the discussion it was suggested that the bands were formed at the rate of two a year and reflected some aspect of equinoctial circulation, perhaps a series of spring and fall diatom pulses. It may be objected that when the band series began Linsley Pond was an oligotrophic lake in a region of cool climate and that such lakes, at least in the Austrian Alps (Findenegg, 1935, p. 408) are known to have only a single diatom pulse per year. When the band series ended Linsley Pond was a eutrophic lake in a region of warm climate and might be expected to have a number of irregular plankton pulses each year, as Lake Mendota in Wisconsin (Birge & Juday, 1922, p. 59, 60) does at the present time.

Let us see how much distortion would be introduced into the results if, at the bottom of the banded zone, each band represented one year and at the top each band represented one-fifth of a year.

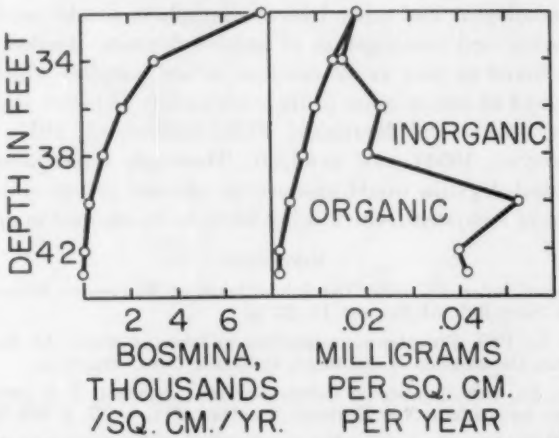

Fig. 4. *Bosmina*, organic matter and inorganic matter per square centimeter per year, calculated from the data of Deevey (1942) and Vallentyne and Swabey (1955) on the assumption that the rate of formation of the bands varied regularly from one per year at 44 feet to five per year at 32 feet.

Figure 4 is a plot of the principal properties based on this assumption. The decrease in inorganic matter deposited per year would be much less striking under these conditions than it would be if the rate of band formation remained constant (fig. 2). It nevertheless remains the most prominent feature of the banded zone. The organic matter per centimeter, for example, increases only about 0.018 milligrams from 43 feet to 32 feet, while the inorganic matter decreases about 0.025 milligrams.

It should be noted that this condition represents an extreme case. It is doubtful that five diatom pulses a year would show up in the sedimentary

record as discrete bands. If the bands were not, as the author believes, laid down at a constant rate, the variation in their rate of deposition was probably a good deal less than five-fold, and the importance of the decrease in inorganic sedimentation correspondingly greater than that shown in figure 4.

CONCLUDING REMARKS

The logarithmic increase in the biomass of the Linsley Pond biocoenosis that occurred during the deposition of the banded gyttja was associated with a logarithmic decrease in the rate of mineral sedimentation. This decrease was probably due to changes in erosion of the catchment area associated with the postglacial amelioration of climate. At the bottom of the banded zone the high mineral content inhibited the regeneration of nutrients but as the mineral content declined nutrient regeneration became more and more complete.

These considerations are all based on the rate of formation of the brown bands. If the bands were not formed at a constant or moderately variable rate the argument falls; until such time as the chronologic validity of the bands is established it must totter a little from lack of support. In any case its application is limited by the shortness of the band sequence.

Paleolimnologists and other lake stratigraphers should bend every effort to the discovery and investigation of banded deposits. Banded gyttja is not likely to be found as long as we continue to use samplers which disturb the deposits, instead of one or other of the wide variety of better samplers (Reissinger, 1936; Jenkin and Mortimer, 1938; Kullenberg, 1947; Livingstone, 1954; Vallentyne, 1954) now available. Thorough investigation of a deep deposit of banded gyttja would produce an advance in our understanding of the evolution of ecosystems which is not likely to be attained in any other way.

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EXPERIMENTAL BREAKAGE OF *BOSMINA* EXOSKELETONS IN A MEDIUM OF WATERY MUD

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ABSTRACT. Shaking wet lake mud for nine hours, and grinding with mortar and pestle both caused an increase in the ratio of separated to attached *Bosmina* antennae contained in the mud. The former treatment caused no change in the ratio of *Bosmina* heads to shells, while the effect of the latter appeared to depend on the duration of grinding. The relative increase of separated antennae in shaken mud samples was caused by breakage against the wall of the container. It is concluded that the breakage zone in a previously described sediment profile from Linsley Pond, Connecticut, was not caused by breakage alone, but also by selective transport of small broken pieces from shallow to deep water by wind-induced currents.

INTRODUCTION

The dead bodies and molted exoskeletons of the fresh-water cladoceran *Bosmina* sink with other dead sestonic material to become part of the bottom mud. *Bosmina* is a characteristic member of the sediment thanatocoenose in lakes (Deevey, 1942; Frey, 1955). There is however one characteristic difference between the living and the fossil forms: in the latter the anterior or head end (with rostrum and two antennae) is usually dissociated from the posterior or shell end (containing other appendages). On the reasonable assumption that *Bosmina* exoskeletons are sedimented intact, one would expect to find 1:1 ratios of head to shells in the sediment. It was therefore with surprise that Vallentyne and Swabey (1955) reported the discovery of a "breakage zone", which had head/shell ratios consistently above unity. This zone was located in the lower part of the C1 pollen zone (approximately 7500 years old) in a sediment profile from Linsley Pond, Connecticut. The breakage zone was also characterized by a high ratio of separated to attached antennae (i.e., broken to intact heads), relatively high breakage of *Pinus* pollen grains and *Plumatella* (Bryozoa) statoblasts (Vallentyne and Swabey, 1955) as well as diatom tests (Patrick, 1943). The work reported here was an attempt to reproduce conditions which might have induced such breakage. The *Bosmina* specimens contained in lake mud were used as the experimental material. This work was supported by the Ontario Research Foundation.

METHODS AND MATERIALS

The mud used in all experiments was collected at 16 m depth from Little Round Lake, Oso County, eastern Ontario. The mud was about 40 percent organic, black in appearance, and with essentially no sand-sized grains.

For the grinding experiment a small amount of wet mud (boiled 10 minutes) was ground with a mortar and pestle for 30 minutes. A sample of the original mud and samples taken after 5, 15 and 30 minutes of grinding were removed for counting purposes. In the shaking experiment, the wet mud was first diluted 1:1 with water and heated on a boiling water bath for 10 minutes in order to loosen up the mud. Samples (70 ml) of the mud-water mixture

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were shaken in 250 ml Erlenmeyer flasks. The stoppered flasks were shaken for varying periods of time on a Burrell Wrist Action Shaker (Model BB), using the maximum swing.

Samples were removed from the mud with a wide-mouthed medicine dropper while the flask was being agitated. Drops of mud were mixed with glycerine, mounted on a glass slide with cover-slip and the *Bosmina* parts counted microscopically (magnification 100×). A minimum of 300 shells (each with two valves) was counted for each sample. Usually three to six slides sufficed to give this number of shells. Counts were recorded separately for heads with two antennae, heads with single antennae, single antennae and shells. Antennae were counted only if they possessed the short medial spines which are characteristic of *Bosmina*. Vallentyne and Swabey (1955) incorrectly referred to the antennae as antennules, an error which is corrected here. Shells were counted only if the mucrones were present, regardless of the amount of breakage of the shell.

RESULTS

Grinding.—We shall report single antennae and heads with single antennae collectively as separated antennae (H_1), and heads with two antennae as attached antennae (H_2). The results of the grinding experiment are reported in table 1. The ratio (H_1/H_2) of separated to attached antennae increased with the duration of grinding, but there was no consistent change in the ratio of heads ($H = H_2 + 1/2\ H_1$) to shells (S). A relative increase in the number of separated antennae would be expected as a result of any process that induced breakage of *Bosmina* heads. The apparent rise and then decline in the H/S ratio is without explanation.

TABLE 1

The Effect of Grinding with a Mortar and Pestle on *Bosmina* Exoskeletons Contained in Wet Mud. H_2, Attached Antennae; H_1, Separated Antennae; S, Shells.

Sample	Ground (min.)	H_2	H_1	S	H_1/H_2	H/S
1	0	360	21	398	0.06	0.93
2	5	235	87	301	0.36	1.26
3	15	138	118	319	0.86	0.62
4	30	118	216	320	1.84	0.71

Shaking.—An initial experiment was performed in which samples were removed at varying time intervals from a flask of mud shaken continuously for 56 hours. Since there did not appear to be any consistent change in the proportion of *Bosmina* parts after more than a few hours, we selected nine hours as the duration of shaking for the dilution experiment described below.

For the dilution experiment, 140 ml of a boiled mud-water mixture (1:1) was placed in a flask. Serial dilutions of mud were prepared such that there were seven flasks, each filled with 70 ml of fluid, but each succeeding flask with only half the mud content of the preceding.

The data for the original mud-water mixture and the seven shaken flasks are presented in table 2. Chi² tests on the individual and total counts for heads and shells showed that none of the H:S ratios differed significantly from a 1:1 ratio ($P = 0.1$). We are justified then in saying that these data do not support the hypotheses that shaking and/or dilution of mud with water affects the H/S ratio. On the other hand, the H_1/H_2 ratio for the sum of all counts from shaken flasks was just significantly different ($P = 0.05$) from the H_1/H_2 ratio of the untreated mud. This suggests that shaking may result in a slight increase in the relative number of separated antennae (probably by separating those which loosely adhere together).

TABLE 2

The Effect of Shaking Serial Dilutions of Mud on *Bosmina* Exoskeletons Contained in the Mud. H_2, Attached Antennae; H_1, Separated Antennae; S, Shells.

Sample	Hours Shaken	Dilution	H_2	H_1	S	H_1/H_2	H/S
0	0	none	598	77	672	0.13	0.95
1	9	none	330	65	403	0.20	0.90
2	9	1/2	324	58	341	0.18	1.03
3	9	1/4	302	66	329	0.22	1.02
4	9	1/8	302	49	333	0.16	0.98
5	9	1/16	310	42	324	0.14	1.02
6	9	1/32	276	44	314	0.16	0.95
7	9	1/64	338	57	367	0.17	1.00

Let us now question whether the increased H_1/H_2 ratio resulted merely from shaking alone or whether it was also affected by the proportions of mud and water in the series of shaken flasks. In order to test if there was any effect of mud dilution on the H_1/H_2 ratio, the hypothesis was selected that the proportions of H_1 and H_2 in samples 1 to 9 should be in the ratio of 148 H_1: 852 H_2, i.e. the ratio of the sums of H_1 and H_2 for samples 1 to 9. Chi² tests on the individual samples showed that none differed significantly ($P = 0.1$) from the expected. While this test is not very rigid, one can also note that there is no general trend in the H_1/H_2 ratios accompanying dilution of the mud. These data do not support the hypothesis that dilution of the mud affects the H_1/H_2 ratio. It is apparent that the increased H_1/H_2 ratios of the shaken flasks as compared to the unshaken were probably caused by breakage against the walls of the flask rather than grinding of *Bosmina* heads against the mud particles.

DISCUSSION

With reference to the meaning of the breakage zone in the Cl sediments of Linsley Pond, Connecticut, the above data suggest this: if the Linsley Pond breakage was mechanical (as appears reasonable because of the diversity of the broken biota) it was probably due to the rupture of *Bosmina* specimens against surfaces their own size or larger. It is unlikely that turbulence in the water could alone induce breakage of *Bosmina* exoskeletons. The ratio of water volume to hard bottom surface for Linsley Pond (or any lake) is enor-

mous as compared to the flasks used in the shaking experiments described above, and the amount of mechanical breakage of *Bosmina* skeletons induced in any lake should, therefore, be small. Although intact heads and shells do actually outnumber those broken in the Cl breakage zone, we are still left with the problem of explaining why the lower Cl sediments show more breakage than is characteristic of other parts of the profile. Our previous suggestion (Vallentyne and Swabey, 1955) that the breakage resulted from an increased turbulence (with consequent grinding) at the mud-water interface is no longer tenable. The most acceptable explanation is the alternative proposed by Vallentyne and Swabey (1955): that breakage alone was not the important factor, but breakage in conjunction with a selective transport of broken parts from shallow to deep water. The broken parts, by virtue of their small size, sink more slowly than intact heads or shells (Vallentyne and Swabey, 1955). Attention then must be focussed on factors which would increase the redeposition of small materials from shallow to deep water. Slope-dependent density currents cannot be the sole explanation since the bottom slope of the lake was not maximal when the lower Cl sediments were deposited. The most important factor must have been wind-induced turbulence. This would act to redistribute the smaller and lighter materials of shallow water deposits throughout the lake. Assuming the same density for different parts of *Bosmina* exoskeletons, the smaller parts would be more effectively carried to the middle of the lake (the site of the LV profile taken by Vallentyne and Swabey). After cessation of the wind, the parts suspended in the middle of the lake would sink to become incorporated in the deep sediment. If this interpretation is correct then one would expect to find evidence of similar Cl breakage zones in neighboring lakes of the district. No one has investigated this possibility as yet.

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ESSAY REVIEW

Science and Civilisation in China, Vol. 2; History of Scientific Thought; by JOSEPH NEEDHAM with the research assistance of WANG LING. P. xxiv, 696. New York, 1956 (Cambridge University Press, $14.50).—The day has come when the reading is completed, and the reviewer rests his weary head and ponders. In forty years, he recalls a no more exhausting literary exercise, but it has not been without its rewards, even considerable ones in certain areas of intellectual reflection. In a sense, this second publication of Needham's seven-volume series continues as an introduction to his survey of science in China, but whereas the first comprised a prolegomenous miscellany of uneven character, this is well-butchered meat with a footnote on every bit of the discarded carcass.

Apart from the sixty-page bibliography, tasty and invaluable brisket, and the excellent index which adds over forty more pages, most of the book deals directly with the various schools of Chinese philosophy. Other sections survey philosophical, but more general, subjects such as *The Fundamental Ideas of Chinese Science, The Pseudo-Sciences and the Skeptical Tradition, Buddhist Thought,* and *Human Law and the Laws of Nature in China and the West.*

Although, in theory, the author is examining the relation of Chinese philosophy to the development of scientific thought, the connection is often so negative that one has the reaction of coming upon essays only tenuously related, if related at all. The fact that these essays are based on the vast scope of data accumulated by a scholar who has obviously been devoted to the intellectual history of the West before turning to that of that East—and a scholar of magnificent memory and universal viewpoint—gives them a juiciness and texture worthy of the most demanding gourmet. The offering is unevenly flavored, however, for the author is definitely prejudiced.

Prejudices, as such, are almost inevitable, and when deftly sprinkled, provide desirable spice on one's food, but Mr. Needham has overseasoned his repast. To present early Confucianists as though they were a self-conscious aggregate of right-wing Tories may be enjoyed as a gastronomic novelty, but to go on to describe the Taoists as "conducting a socialist holding action for two thousand years" (p. 60) is spoiling the meat. That we are not dealing with an incidental, verbal flurry is borne out again and again by the unquestioning assumption of an evolutionary theory of culture involving stages such as that of communal ownership before that of private property (*e.g.* pp. 104-5, 543). That the acceptance of such notions is generally associated with the lag of social science in the Soviet Union is significant, but not to the point. It is the correlation of Taoist thought with such a view, whether true or false, that from the eyes of this reviewer appears to be naïveté, Hou Wai-lu's interpretation of the *Tao Tê Ching* not withstanding, but, on the contrary, exemplifying (p. 110).

If this is a trivial matter, considering all that is encompassed in the volume, it leads one to reflections concerning the whole. Again one is impressed by the orderly analysis and regrouping of diversely found data, as demonstrated by the amazing forty-page treatise on the *I Ching.* On the other hand, when the reviewer examines his total reactions, he concludes that in this work objectivity is often more presumptive than real, that judgments tend to be

authoritarian, that the data are infrequently allowed to speak for themselves. This is not his reaction to Fung Yu-lan's *A History of Chinese Philosophy* which may be advantageously studied in conjunction with the volume under review, nor, again, to the compendious essays of Berthold Laufer, true paterfamilias of the household of footnotes. In seeking the reason, it would be too simple to say that one can step too abruptly from the relatively objective realms of science into a realm where too facile theorizing is a virus not easily recognized or removed. The problem is more philosophical. Mr. Needham shows genius in slicing up descriptive data, and his speculations are often exciting; it is just that his conceptual knives and choppers are philosophically Western, pro-Whiteheadian, and not of the *genre* Chinese. We can presume this will matter less, or hardly at all, when Mr. Needham begins in future volumes to serve us plain yet satisfying dishes, such as a thick soup of *Mathematics* or buttered *Engineering, Mainly Mechanical.*

CORNELIUS OSGOOD

REVIEWS

Minerals and the Microscope; by H. G. SMITH, revised by M. K. WELLS. P. x, 148; 23 text figs., 12 pls. (one colored). New York, 1956 (MacMillan Co., $3.00).—This little textbook covers in a 6-page chapter the microscope and its parts; in four more chapters (60 pp.) its uses for studying thin sections of minerals; in four more (70 pp.), the nature of rock-forming minerals and their systematic description. Seven general references are cited on p. 143, and an index of about 400 items supplements the text.

Although the text seems too short for a thorough course in optical mineralogy and petrography, it may be welcomed by instructors giving a short introduction to the subject as part of a general course including several related fields. The descriptions of minerals will hardly be sufficient for identifications without supplementary books of procedures and tables of optical properties. The introduction to microscopy may be more useful, even though its shortness precludes descriptions of many good techniques and necessitates such abbreviated summaries of crystal optics that it omits or scarcely mentions the reasons for some of the important phenomena observed [on p. 65, for example, omitting the principal reason—namely, variation of birefringence with orientation—for the production of higher interference colors near the margin of a centered uniaxial interference figure than near the melatope].

HORACE WINCHELL

Elementary Crystallography (An introduction to the fundamental geometrical features of crystals); by M. J. BUERGER. P. xxiii, 528, illus. New York, 1956 (John Wiley & Sons, Inc., $9.50).—In this book the author is mostly concerned with giving a full derivation of the 32 crystal classes (point groups) and the 230 space groups. After several preparatory chapters on repetition theory, translation periodicity and symmetry, the crystal classes are derived in just nine pages of chapter 5. An alternative derivation, involving the use of the Schoenflies notation, is given in chapter 6. In the next two

chapters the plane lattices and the space lattices are derived. Chapter 9, devoted to the coordinate systems of crystallography, is notable for its careful treatment of the setting of triclinic crystals (pages 107 to 111). This has long been needed in a textbook and is most welcome but might be greatly simplified without loss of rigor or generality.

Chapter 10 (57 pages) deals with crystal forms. Each of the 32 classes is treated, the symmetry being pictured by means of orthographic drawings of the spherical projection of the general form for each class. There are numerous crystal drawings on which the faces are designated by letters. These are not explained and there is no reference to numerical face or form indices in the text, letter indices only being used in the summary tables for each system. In the section on the isometric system numerical indices of crystal faces do appear on some of the drawings. Though form names are used, the classes are designated only by symbols. The so-called "first setting", taking the 2 or $\bar{2}$ direction as *c* axis, is used in the monoclinic system in spite of the "decision of the International Union of Crystallography" that "the 2nd setting is accepted as standard for morphological and structural crystallographic studies." The choice of reference axes is not indicated on the symmetry diagrams of chapter 10 but may be deduced from the tables of forms given for each crystal system. These tables continue the old convention of making rhombohedrons in the class $32/m$ first order forms and comparable conventions in the classes $3m$, 32, $\bar{6}2m$ and $\bar{4}2m$. This would require the use of multiple cells for the crystals in certain space groups, a situation that would have deserved explicit statement. Compare, for instance, the space groups D_{3d}^1 - P$\bar{3}$1*m* and D_{3d}^3 - P$\bar{3}$*m*1 or D_{2d}^1 - P$\bar{4}$2*m* and D_{2d}^5 - P$\bar{4}$*m*2.

Chapter 11, on the determination of crystal class, is written entirely from the viewpoint of the X-ray crystallographer. This leads to a brief treatment of those properties of crystals whose consideration is a common adjunct to space group determination. At the top of page 188 it is stated that pyroelectricity is "permitted to crystals belonging to the 21 acentric classes." Similar statements can be found in other texts. However, in the International Tables for X-ray Crystallography (1951, p. 41) it is stated in agreement with W. Voigt (Lehrbuch der Kristallphysik, 1910, p. 234) that pyroelectricity can exist only "where there is a unique polar axis in the point group". There are ten such point groups.

Chapter 12, on the algebra of operations, is followed by four chapters, making up nearly half the volume, in which all the space groups are derived. Symmetry diagrams are given for each space group, even those in the isometric system for which no diagrams appear in the International Tables of 1951. Moreover, the diagrams in Buerger's book are larger by a factor of 1.5 or more. Chapter 16 closes with a sequence of ten text-free pages occupied by symmetry diagrams for the ten space groups of class m3m. This is followed by 3 short chapters devoted to a résumé of space groups, equivalent positions, and space group determination.

The book is concluded by three chapters on group theory which the author in his preface refers to as "a kind of appendix". Chapter 20 deals with some of the concepts of group theory. In chapter 21 these are applied to the

derivation of point groups and their subgroups, a third full derivation of the crystal classes being given. Unfortunately the headings of all odd-numbered pages from 495 to 513 read "*Group theory applied to joint* (sic) *symmetries*". The last chapter of only ten pages gives just a suggestion of how group theory may be applied to space symmetries.

The table of contents is most detailed, extending to more than eight pages, and is followed by a list of the many excellent tables. The index, however, is rather scanty, less than four pages, many subjects being omitted while for others which are treated at several points in the text only a single page reference can be found. A set of a few exercises for students is given at the end of each of the first ten chapters. The number of misprints is very small, a real achievement in a book of this kind.

Most of the content of this book differs from that of other textbooks dealing with crystallography and much of it is original or is presented in a fresh manner. This is admirable, but, while filling in some of the large gaps in the material hitherto available to the student, the author has left untouched many important aspects of crystallography. He has especially slighted what may be termed the tools of the crystallographer. The reciprocal lattice, goniometry, zones and zonal relations, stereographic and gnomonic projection, are not mentioned. Twinning is referred to in chapter 11 only to explain that it will not be dealt with. Axial elements are ignored, even in the chapter on coordinate systems. Schoenflies space-group symbols are omitted though they might easily have been fitted in. Plane groups are not discussed though all 17 of them are pictured on the end papers by means of diagrams of different design than those used on the end papers of the author's "X-ray Crystallography" (1942) for the same purpose. The transformation of indices or coordinates with change of reference axes is left out though the author covered part of this subject in great detail in his earlier book. It almost seems that he chose to leave out everything that has been adequately dealt with before.

A. PABST

Introduction to Microfossils; by DANIEL J. JONES. P. XVII, 406; illustrated. New York, 1956 (Harper and Brothers, Geoscience Series, $6.50).— In writing this text Professor Jones of the University of Utah has filled a conspicuous gap in the roster of references and texts in paleontology for the college undergraduate. The text presents the essentials of micropaleontology with far better balance than has been done before, giving adequate morphologic descriptions for the different kinds of microfossils in proportion to their abundance or usefulness; foraminifera are purposely given outline, but adequate, treatment. Excellent line drawings are used throughout to illustrate the text. In addition to the morphologic and systematic review of the microfossil groups, chapters deal with the collection, preparation, stratigraphy and use of microfossils. Five appendices include information on the microscope, zoological classification and nomenclature, illustration of microfossils and a useful glossary of terms.

With one exception *Introduction to Microfossils* admirably lives up to its purpose of being an elementary text. The exception is the use of a synoptic

classification of organisms which seems a far more elaborate scheme than is either necessary or desirable in an elementary text. This slight difficulty is more than overbalanced by numerous praiseworthy features, not the least of which are the excellent reference lists that accompany each chapter. *Introduction to Microfossils* is a very useful and adaptable text and should receive wide acceptance in colleges and paleontologic laboratories.

KARL M. WAAGE

Annotated Bibliography of Geologic and Soils Literature of Western North Pacific Islands; compiled by HELEN L. FOSTER. P. iv, 879; 5 figs. Washington, 1956 (Office of Chief of Engineers, Corps of Engineers, U. S. Army).—This volume will be of very great usefulness to all those persons interested in the geology or soils of the former Japanese Islands in the Pacific who can obtain a copy. It provides a very complete and intelligently annotated list of Japanese publications on those islands to 1954, plus a less complete list of articles published elsewhere (those can generally be located through the Geological Society of America bibliographies). Miss Foster had the assistance of several Japanese geologists in preparing the bibliography, and most of the annotations were written by Mr. Kinhito Musya and Dr. Ichiro Hayasaka.

JOHN RODGERS

Collections préhistoriques, planches, Album No. 1; with a preface by l'Abbé H. BREUIL. P. 8; 122 pls., 1 map. Paris, 1956 (Musée d'Ethnographie et de Préhistoire Bardo).—These plates were originally prepared to illustrate a synthesis of Northwest African prehistory by M. Reygasse. Sickness having prevented completion of the synthesis, the plates are published by themselves, with a detailed description of each one to compensate for the lack of a text. The specimens illustrated are in the Musée d'Ethnographie et de Préhistoire du Bardo in Algiers. They cover the complete archaeological sequence, beginning with the newly discovered pebble tools of Villafranchian age and continuing through the Paleolithic, Mesolithic, and Neolithic into the Iron Age.

IRVING ROUSE

Dictionary of Anthropology; by CHARLES WINICK. P. 597. New York, 1956 (The Philosophical Library, $10.00).—Contains about 10,000 entries, taken from archaeology, ethnology, linguistics, and physical anthropology. The names of leading anthropologists, artifact types, cultures (but not tribes), and forms of fossil man are included. The definitions are necessarily simple and sometimes fail to convey the total range of a word's meaning but they should be adequate for the non-specialist. IRVING ROUSE

ERRATUM

In the paper by George Tunell: Evaluation of the chemical potential in terms of intensive quantities, in the issue for April, 1957, the last equation on page 264 and the succeeding line belong at the end of footnote 3.

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COMING MAY 22

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